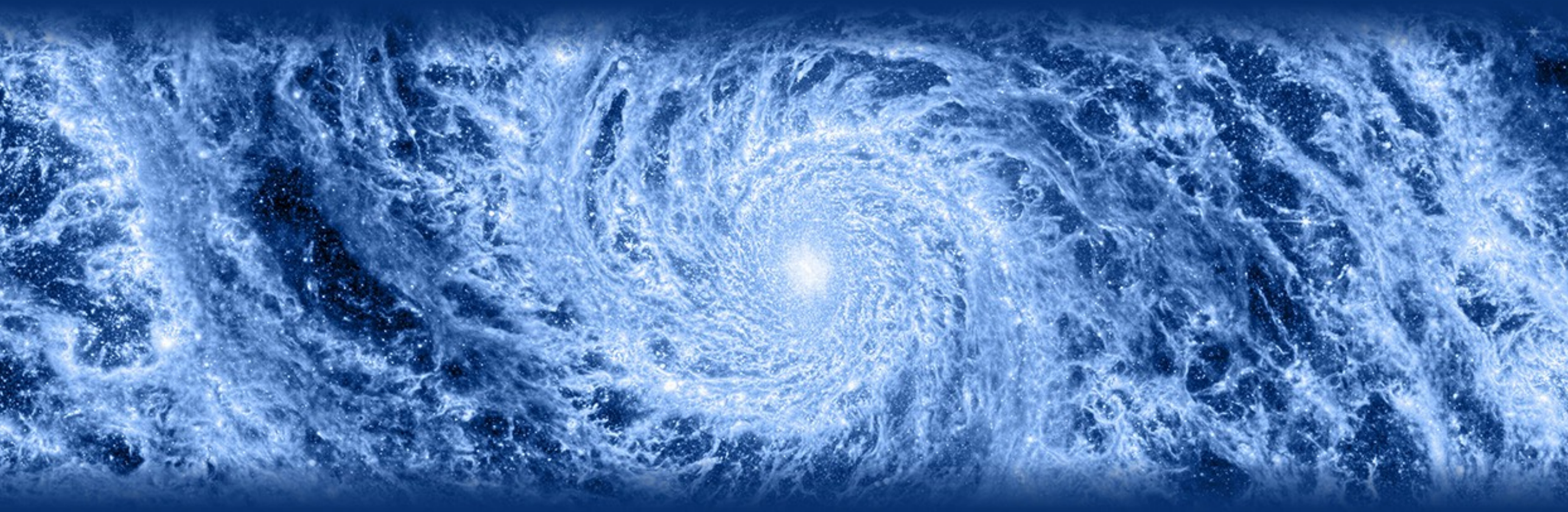
Galaxies

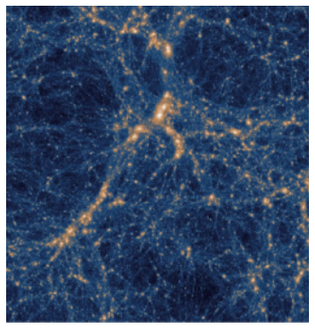
Prof. Benedikt Diemer



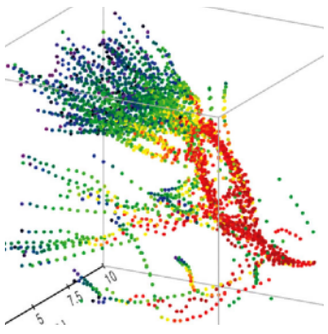
Chapter 8 • The co-evolution of halos, gas, stars, and metals

§8.1 • Semi-analytical models of galaxy evolution

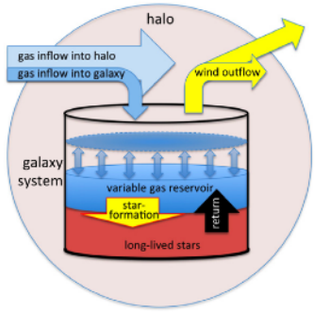
Models of galay formation



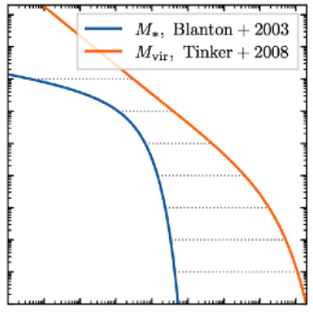
Hydrodynamical simulations



Semi-analytical models



Regulator/bathtub models



Empirical models (abundance matching etc.)

Most complex

Least complex

Merger trees

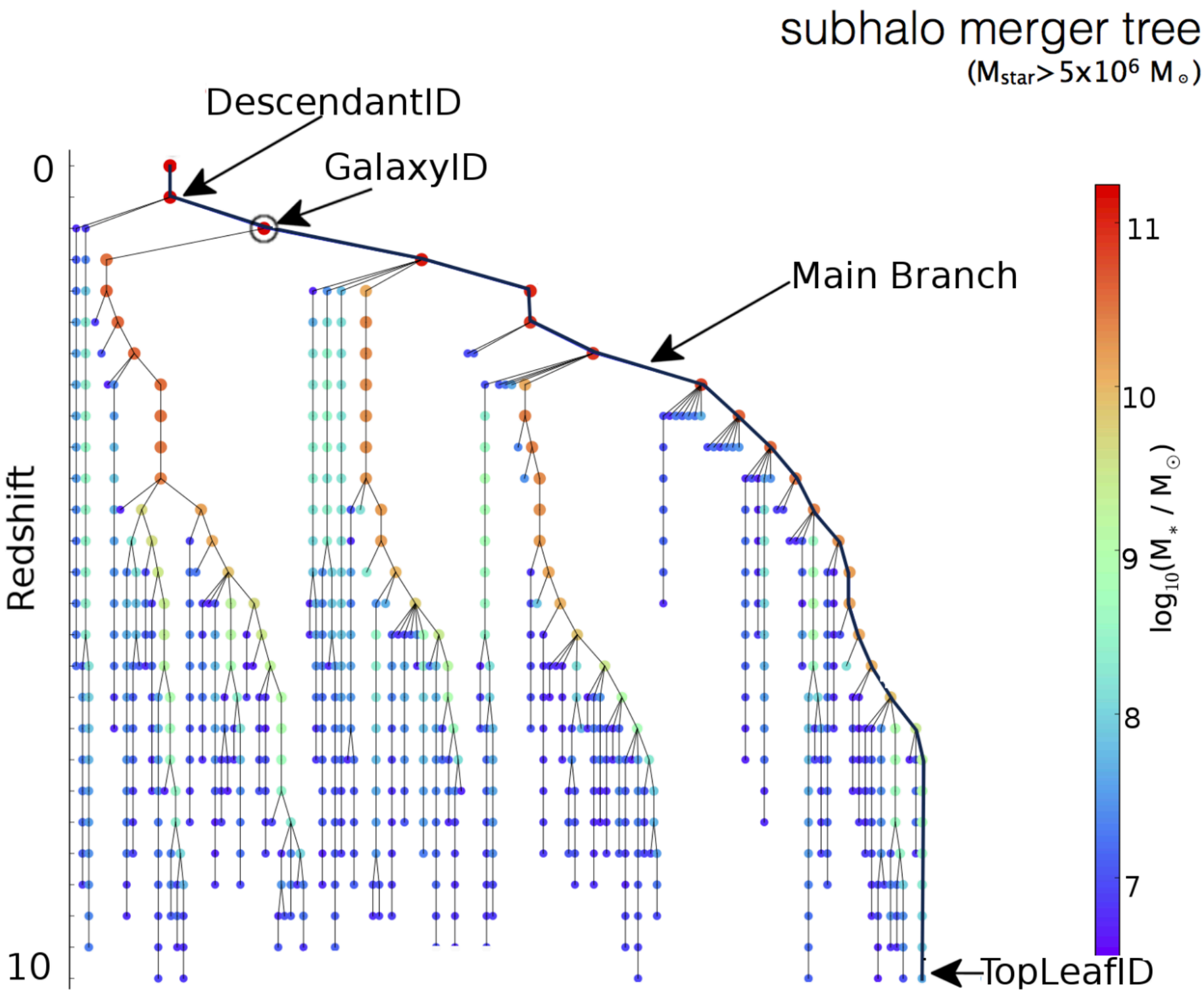
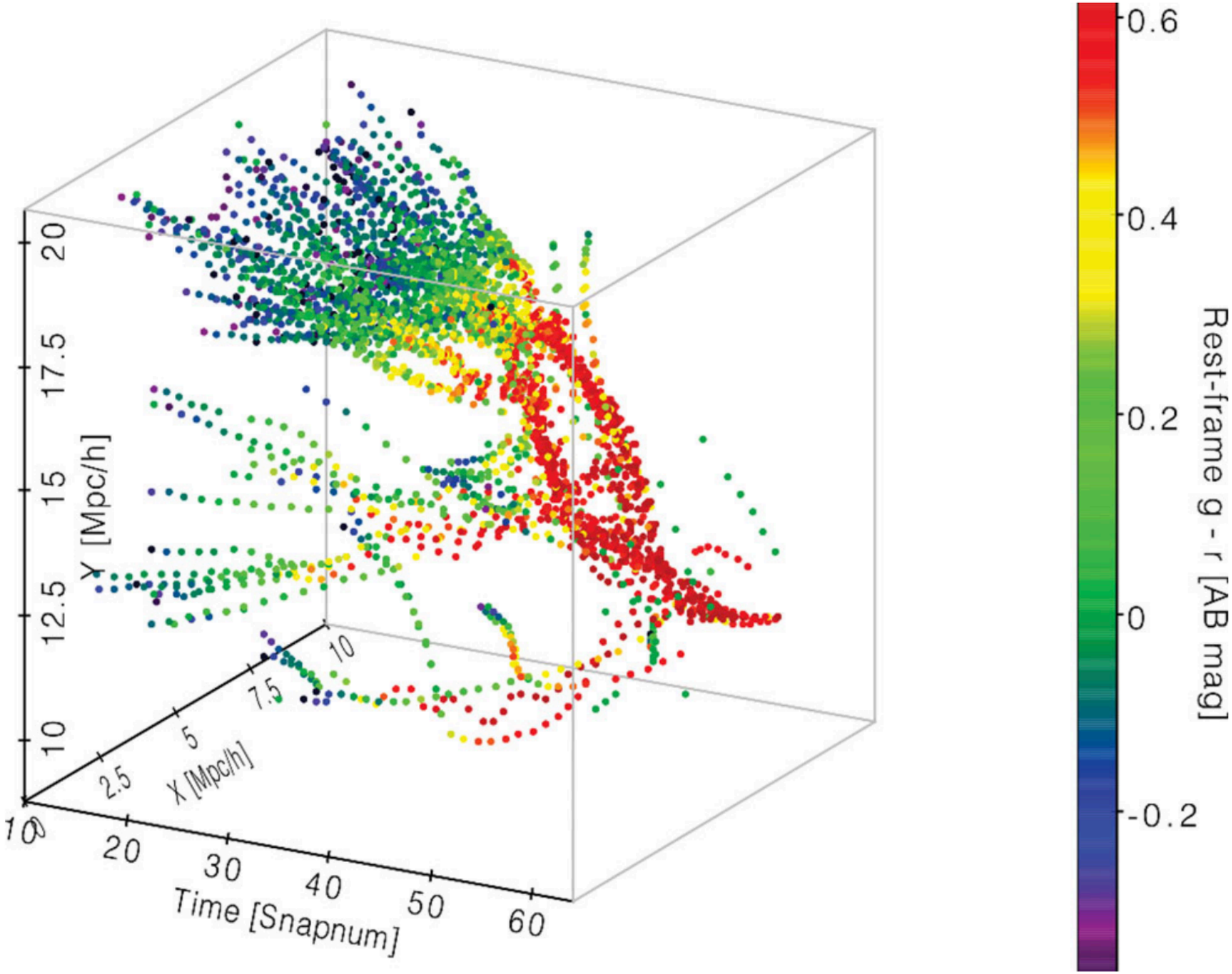


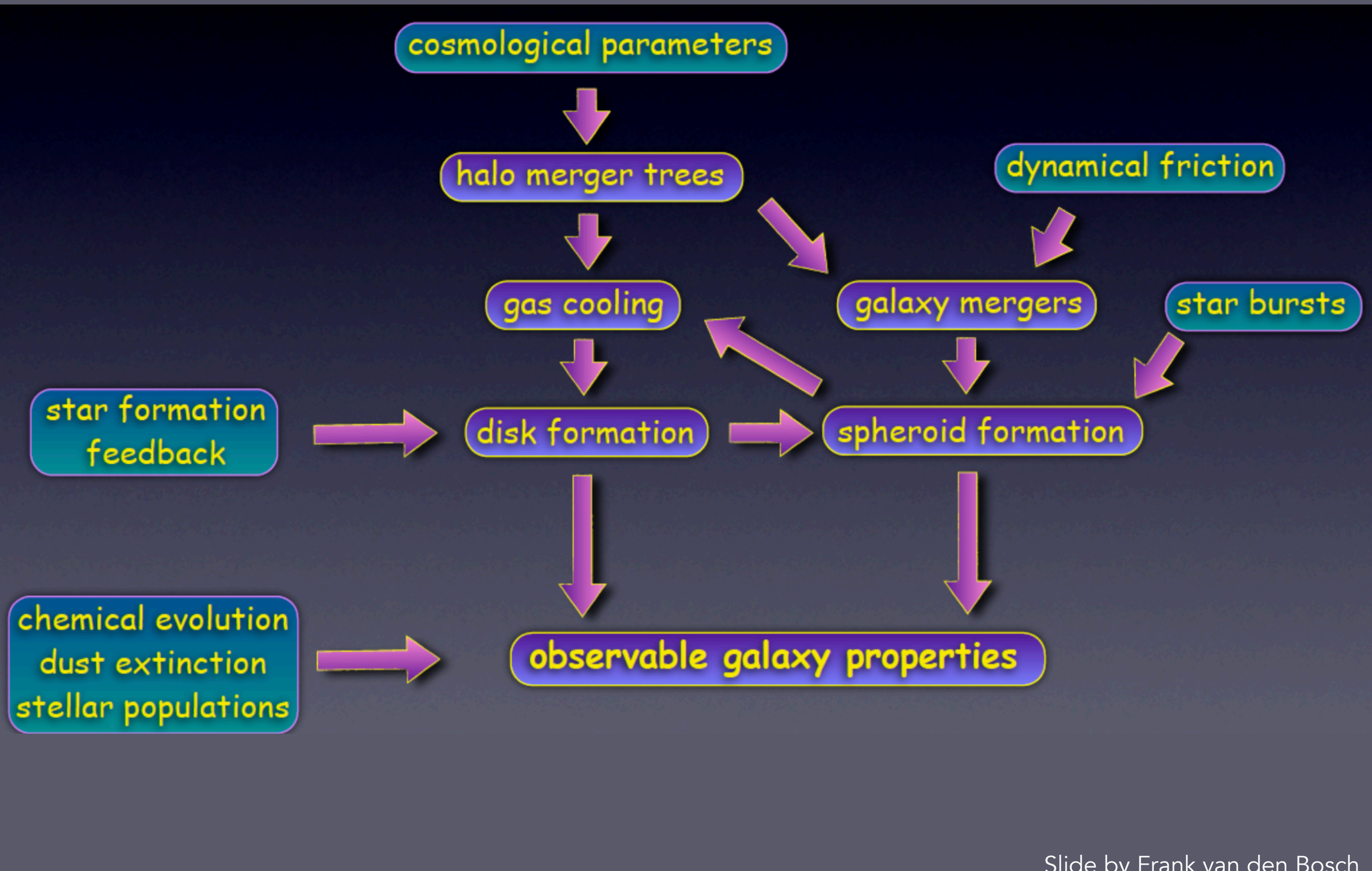
Image by Felipe Ardila

Merger trees



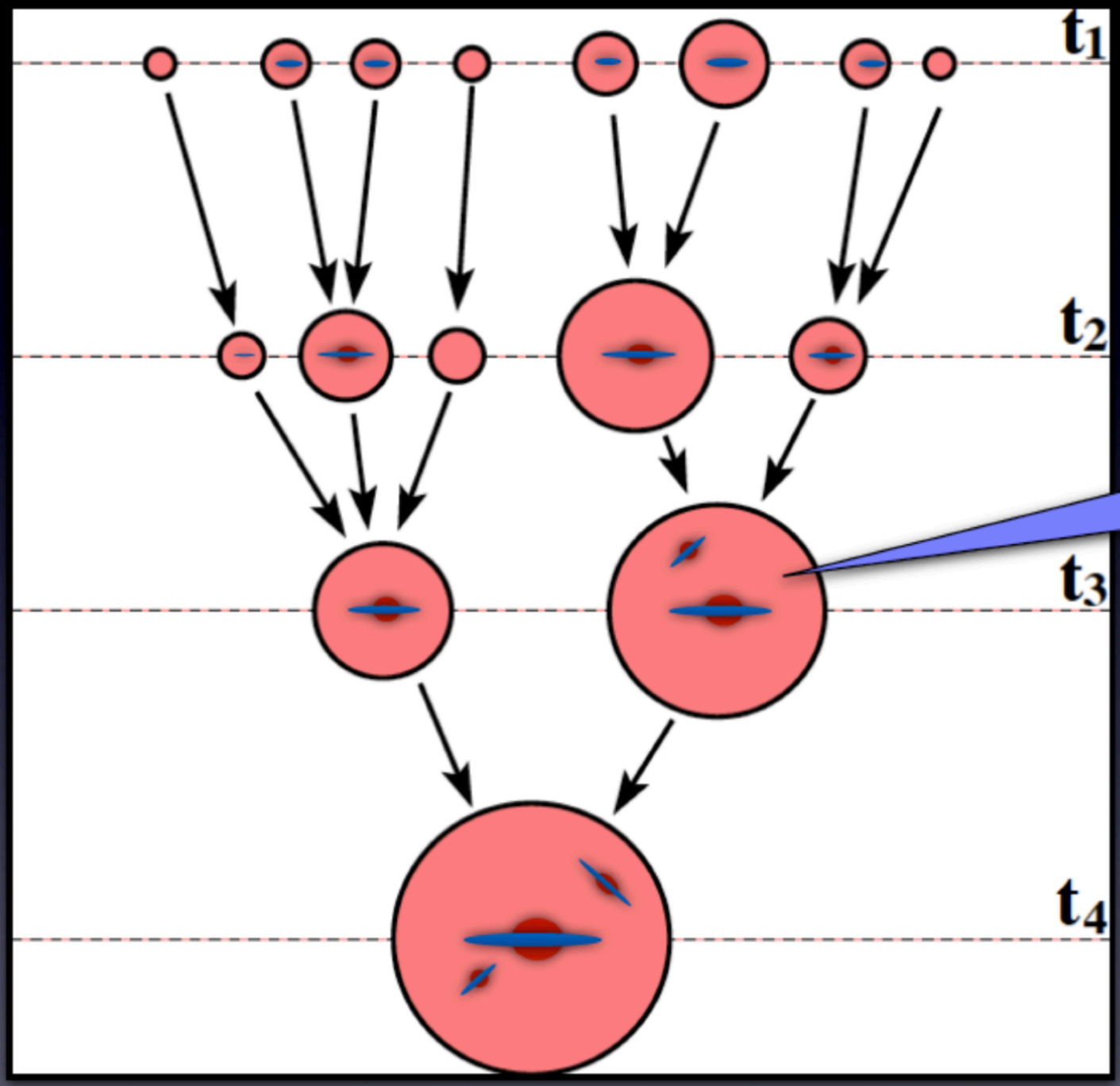
Overzier et al. 2013

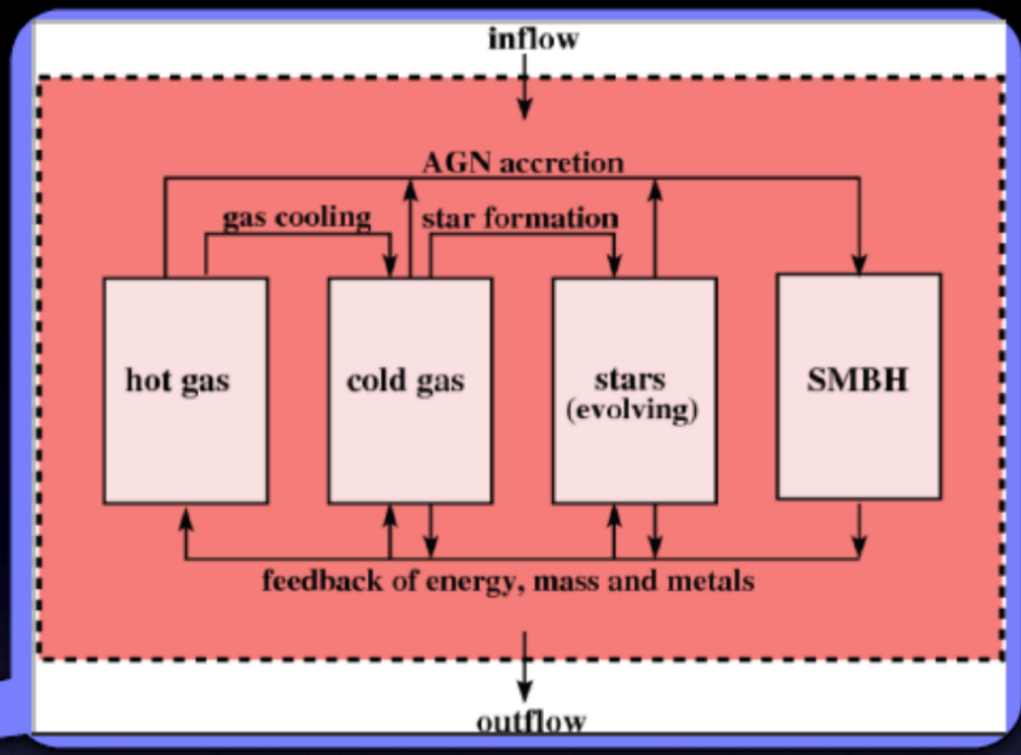
Semi-analytical models



Slide by Frank van den Bosch

Semi-analytical models



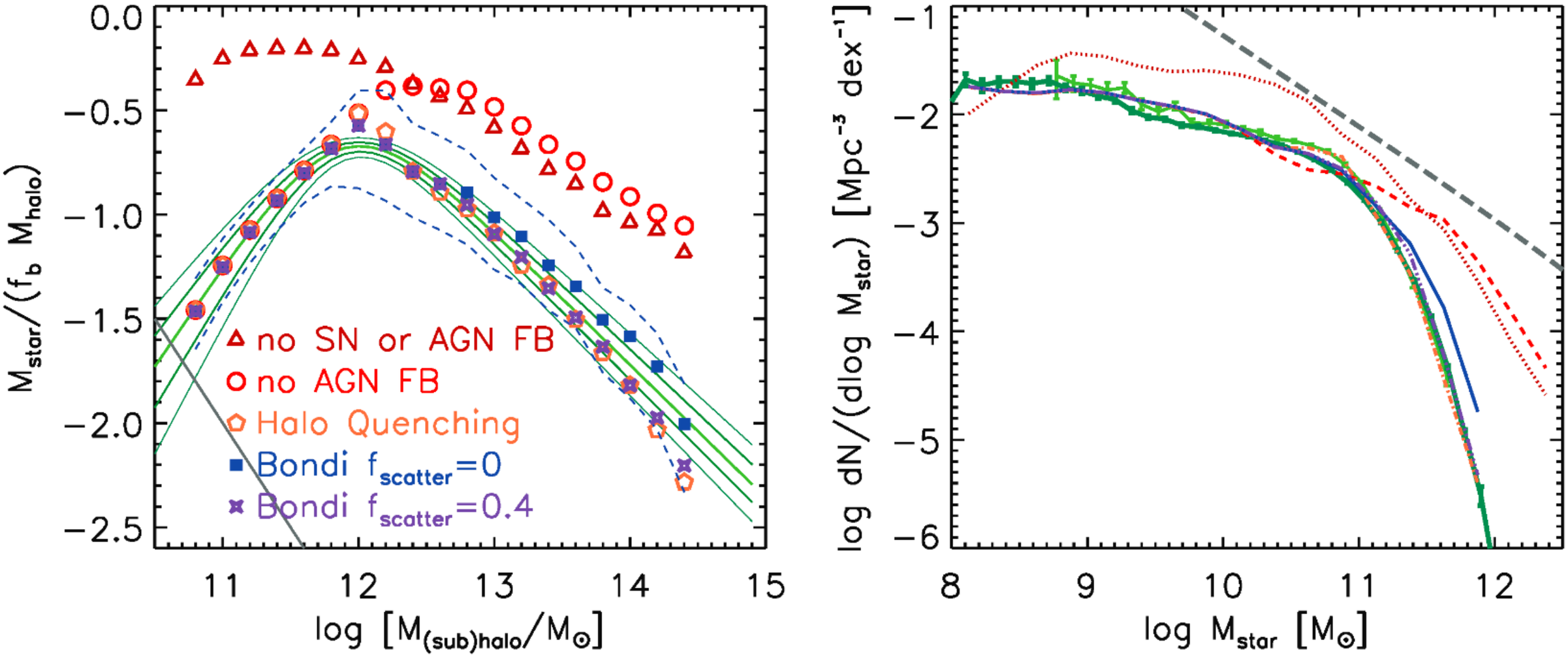


$$M_{\rm vir} = M_{\rm DM} + M_* + M_{\rm cold} + M_{\rm hot}$$
$$\dot{M}_{\rm hot} = -\dot{M}_{\rm cool} + \dot{M}_{\rm reheat} + f_{\rm bar}\,\dot{M}_{\rm vir}$$
$$\dot{M}_{\rm cold} = \dot{M}_{\rm cool} - \dot{M}_{\rm reheat} - \dot{M}_*$$

- $\dot{M}_{\rm vir}$ ⟷ mass accretion
- $\dot{M}_{\rm cool}$ ⟷ cooling
- $\dot{M}_*$ ⟷ star formation
- $\dot{M}_{\rm reheat}$ ⟷ feedback

Slide by Frank van den Bosch

Semi-analytical models



Somerville et al. 2008

Semi-analytical models

Parameter	Description	Fiducial value	Fixed/adjusted
Photoionization squelching (Section 2.3)			
$z_{\rm overlap}, z_{\rm re-ionize}$	Redshift of overlap/re-ionization	11, 10	F
Quiescent star formation (Section 2.5.1)			
$A_{\rm Kenn}$	Normalization of Kennicutt law ($M_\odot$ yr^{-1} kpc^{-2})	8.33×10^{-5}	A
$N_{\rm K}$	Power-law index in Kennicutt law	1.4	F
$\chi_{\rm gas}$	Scale radius of gas disc, relative to stellar disc	1.5	A
$\Sigma_{\rm crit}$	Critical surface density for star formation ($M_\odot$ pc^{-2})	6.0	A
Burst star formation (Section 2.5.2)			
$\mu_{\rm crit}$	Critical mass ratio for burst activity	0.1	F
$e_{\rm burst,0}$	Burst efficiency for 1:1 merger	Equation (9)	F
$\gamma_{\rm burst}$	Dependence of burst efficiency on mass ratio	Equation (8)	F
$\tau_{\rm burst}$	Burst time-scale	Equation (10)	F
Merger remnants and morphology (Section 2.6)			
$f_{\rm sph}$	Fraction of stars in spheroidal remnant	Equation (11)	A
$f_{\rm scatter}$	Fraction of scattered satellite stars	0.4	A
SN feedback (Section 2.7)			
$\epsilon^0_{\rm SN}$	Normalization of reheating function	1.3	A
$\alpha_{\rm rh}$	Power-law slope of reheating function	2.0	A
$V_{\rm eject}$	Velocity scale for ejection of reheated gas (km s^{-1})	120	A
$\chi_{\rm re-infall}$	Time-scale for re-infall of ejected gas	0.1	A
Chemical evolution (Section 2.8)			
y	Chemical yield (solar units)	1.5	A
R	Recycled fraction	0.43	F
Black hole growth (Section 2.9)			
$\eta_{\rm rad}$	Efficiency of conversion of rest mass to radiation	0.1	F
$M_{\rm seed}$	Mass of seed BH ($M_\odot$)	100	F
$f_{\rm BH,final}$	Scaling factor for mass of BH at end of merger	2.0	A
$f_{\rm BH,crit}$	Scaling factor for 'critical mass' of BH	0.4	F
AGN-driven winds (Section 2.1.0)			
$\epsilon_{\rm wind}$	Effective coupling factor for AGN-driven winds	0.5	F
Radio mode feedback (Section 2.1.1)			
$\kappa_{\rm radio}$	Normalization of 'radio mode' BH accretion rate	3.5×10^{-3}	A
$\kappa_{\rm heat}$	Coupling efficiency of radio jets with hot gas	1.0	F

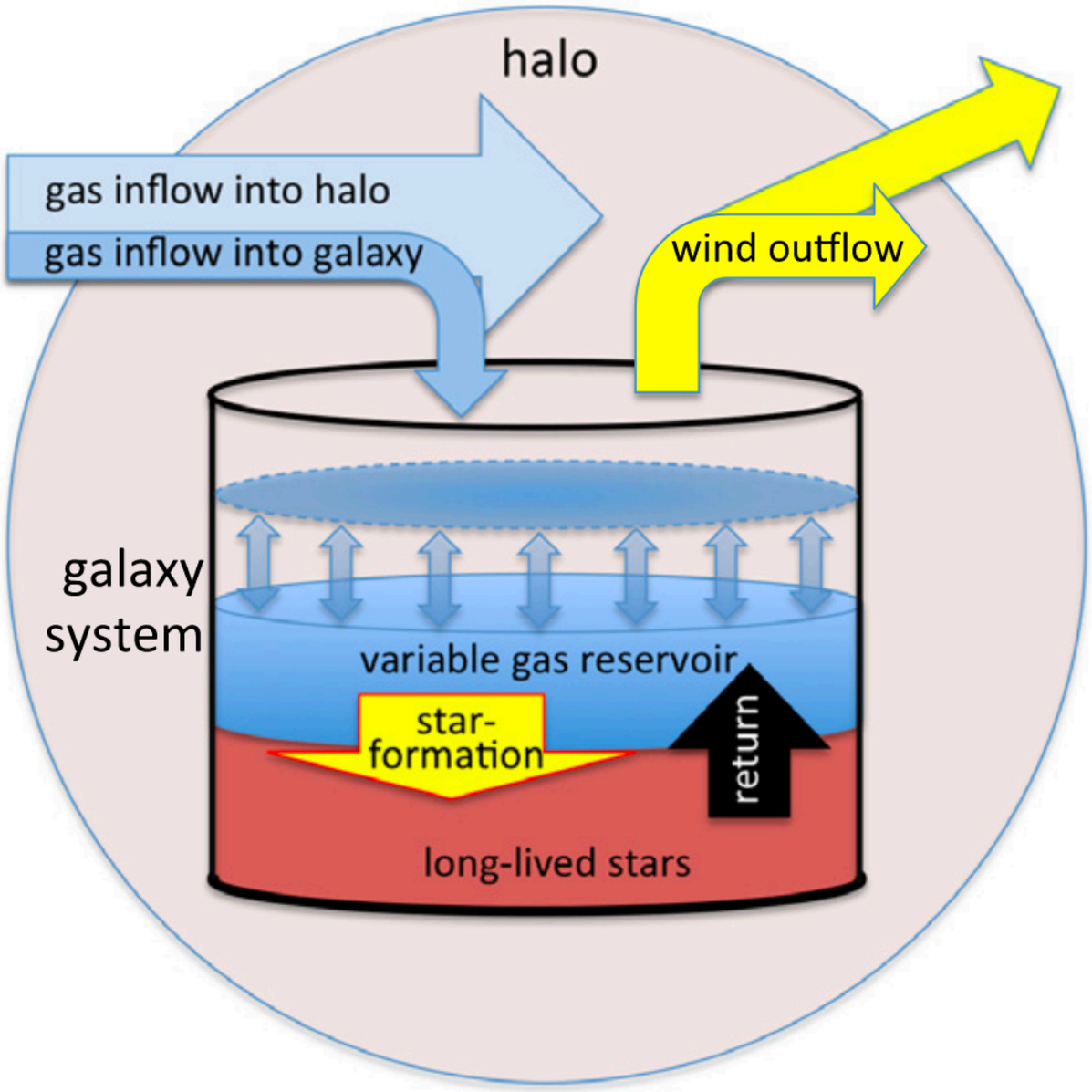
Somerville et al. 2008

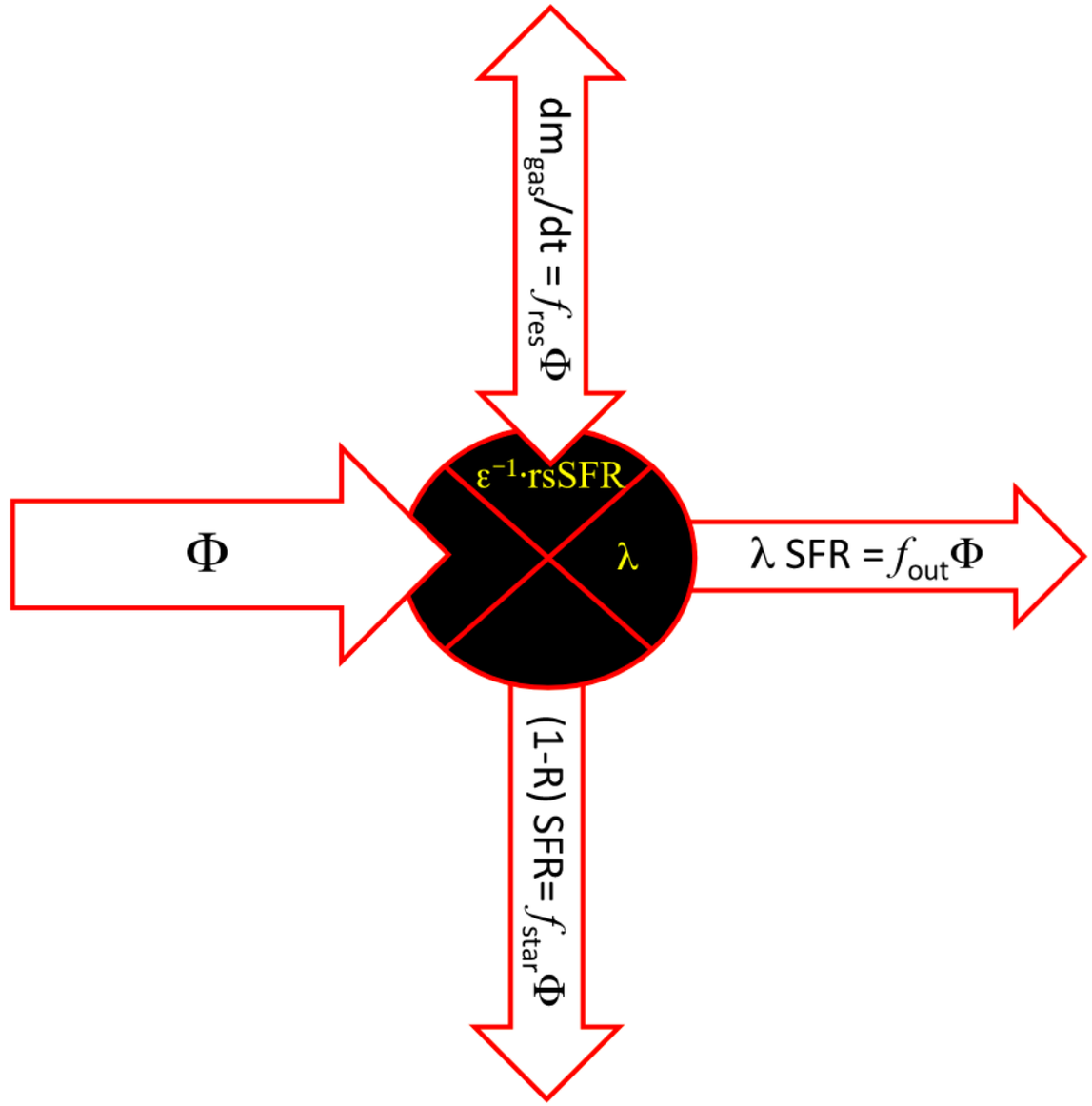
Semi-analytical models

Parameter	Value	Reference
[H_0]	70.2 km/s	Section 4.2; (Komatsu et al., 2010)
[Omega_0]	0.2725	Section 4.2; (Komatsu et al., 2010)
[Omega_DE]	0.7275	Section 4.2; (Komatsu et al., 2010)
[Omega_b]	0.0455	Section 4.2; (Komatsu et al., 2010)
[T_CMB]	2.72548 K	Section 4.2; (Komatsu et al., 2010)
[accretionDisksMethod]	ADAF	Section 4.3
[adafAdiabaticIndex]	1.444	Section 4.3
[adafEnergyOption]	Pure ADAF	Section 4.3
[adafRadiativeEfficiency]	0.01	Section 4.3
[adafViscosityOption]	Fit	Section 4.3
[adiabaticContractionGnedinA]	0.8	Section 4.8
[adiabaticContractionGnedinOmega]	0.77	Section 4.8
[barInstabilityMethod]	ELN	Section 4.7
[blackHoleSeedMass]	100	Section 3.1.2
[blackHoleWindEfficiency]	0.001	Section 3.1.2
[bondiHoyleAccretionEnhancementHotHalo]	1	Section 3.1.2
[bondiHoyleAccretionEnhancementSpheroid]	1	Section 3.1.2
[bondiHoyleAccretionTemperatureSpheroid]	100	Section 3.1.2
[coolingFunctionMethod]	Atomic CIE Cloudy	Section 4.5.1
[coolingTimeAvailableAgeFactor]	0	Section 4.5.5
[coolingTimeSimpleDegreesOfFreedom]	3	Section 4.5.4
[darkMatterProfileMethod]	NFW	Section 4.6.1
[darkMatterProfileMinimumConcentration]	4	Section 3.8.2
[diskOutflowExponent]	2	Section 4.23
[diskOutflowVelocity]	200 km/s	Section 4.23
[effectiveNumberNeutrinos]	4.34	Section 4.4.2
[galacticStructureRadiusSolverMethod]	Adiabatic	Section 4.8
[haloMassFunctionMethod]	Tinker2008	Section 4.4.6
[haloSpinDistributionMethod]	Bett2007	Section 4.6.3
[hotHaloOutflowReturnRate]	1.26	Section 3.2.2
[imfSalpeterRecycledInstantaneous]	0.39	Section 4.12.2
[imfSalpeterYieldInstantaneous]	0.02	Section 4.12.2
[imfSelectionFixed]	Salpeter	Section 4.12.1
[isothermalCoreRadiusOverVirialRadius]	0.1	Section 4.10
[majorMergerMassRatio]	0.1	Section 4.9.1
[mergerRemnantSizeOrbitalEnergy]	1	Section 4.9.2
[mergerTreeBuildCole2000AccretionLimit]	0.1	Section 4.16
[mergerTreeBuildCole2000MassResolution]	5×10^9 $M_\odot$	Section 4.16
[mergerTreeBuildCole2000MergeProbability]	0.1	Section 4.16
[mergerTreeConstructMethod]	Build	Section 4.14
[minorMergerGasMovesTo]	Spheroid	Section 4.9.1
[modifiedPressSchechterFirstOrderAccuracy]	0.1	Section 4.15
[modifiedPressSchechterG0]	0.57	Section 4.15
[modifiedPressSchechterGamma1]	0.38	Section 4.15
[modifiedPressSchechterGamma2]	−0.01	Section 4.15
[powerSpectrumIndex]	0.961	Section 4.4.1; (Komatsu et al., 2010)
[powerSpectrumReferenceWavenumber]	1 Mpc^{-1}	Section 4.4.1; (Komatsu et al., 2010)
[powerSpectrumRunning]	0	Section 4.4.1; (Komatsu et al., 2010)
[randomSpinResetMassFactor]	2	Section 3.7.2
[reionizationSuppressionRedshift]	9	Section 4.1
[reionizationSuppressionVelocity]	30 km/s	Section 4.1
[satelliteMergingMethod]	Jiang2008	Section 4.22.1
[sigma_8]	0.807	Section 4.4.1 & Section 4.4.2
[spheroidEnergeticOutflowMassRate]	1	Section 3.4.2
[spheroidOutflowExponent]	2	Section 4.23
[spheroidOutflowVelocity]	50 km/s	Section 4.23
[spinDistributionBett2007Alpha]	2.509	Section 4.6.3
[spinDistributionBett2007Lambda0]	0.04326	Section 4.6.3
[stabilityThresholdGaseous]	0.9	Section 4.7
[stabilityThresholdStellar]	1.1	Section 4.7
[starFormationDiskEfficiency]	0.01	Section 4.17
[starFormationDiskMinimumTimescale]	0.001 Gyr	Section 4.17
[starFormationDiskVelocityExponent]	−1.5	Section 4.17
[starFormationSpheroidEfficiency]	0.1	Section 4.17
[starFormationSpheroidMinimumTimescale]	0.001 Gyr	Section 4.17
[starveSatellites]	True	Section 3.2.2
[stellarPopulationPropertiesMethod]	Instantaneous	Section 4.18
[summedNeutrinoMasses]	0	Section 4.4.2
[transferFunctionMethod]	Eisenstein + Hu	Section 4.4.2
[virialDensityContrastMethod]	Spherical top hat	Section 4.4.5

Benson 2012

Regulator models

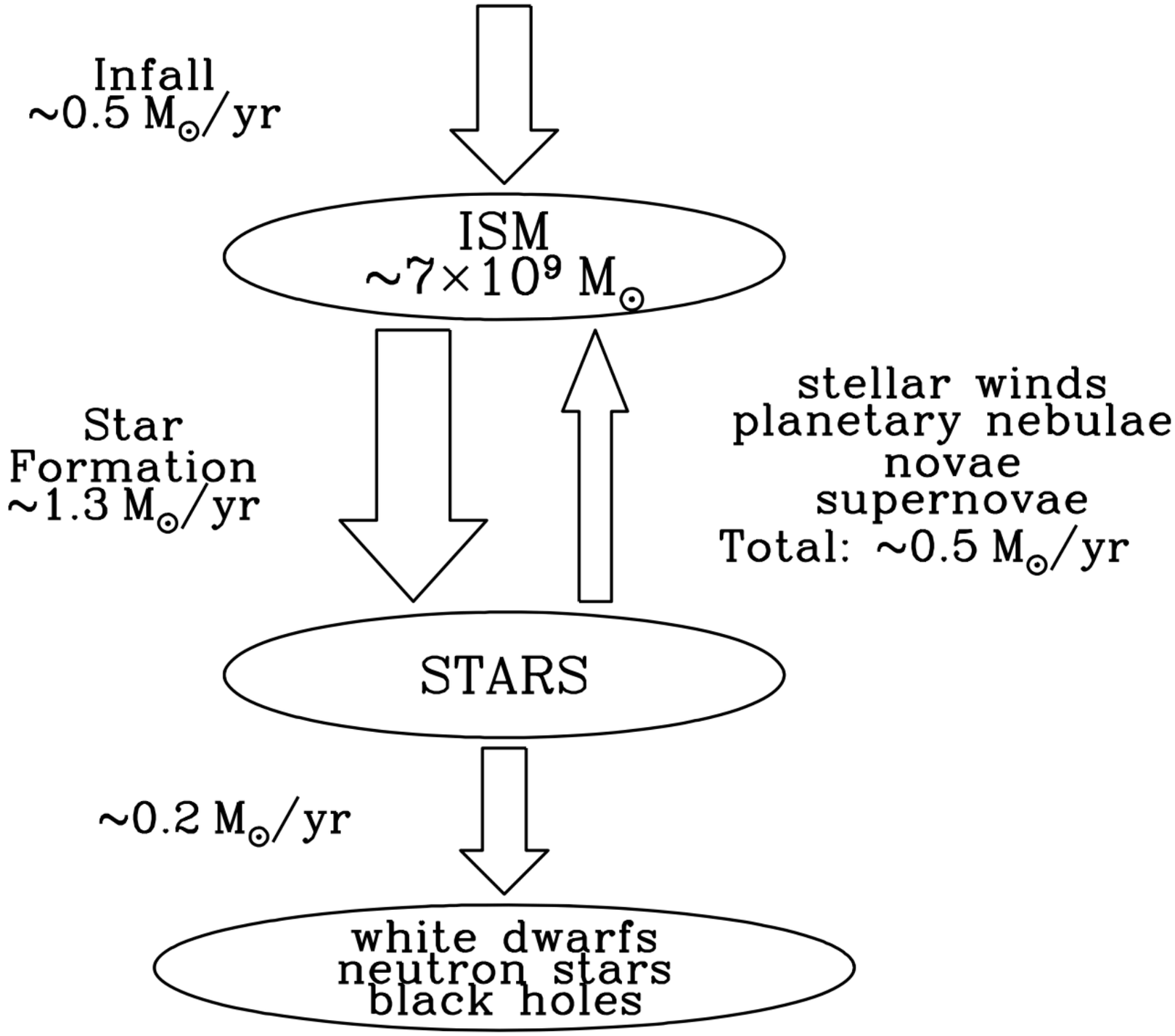




Lilly et al. 2013

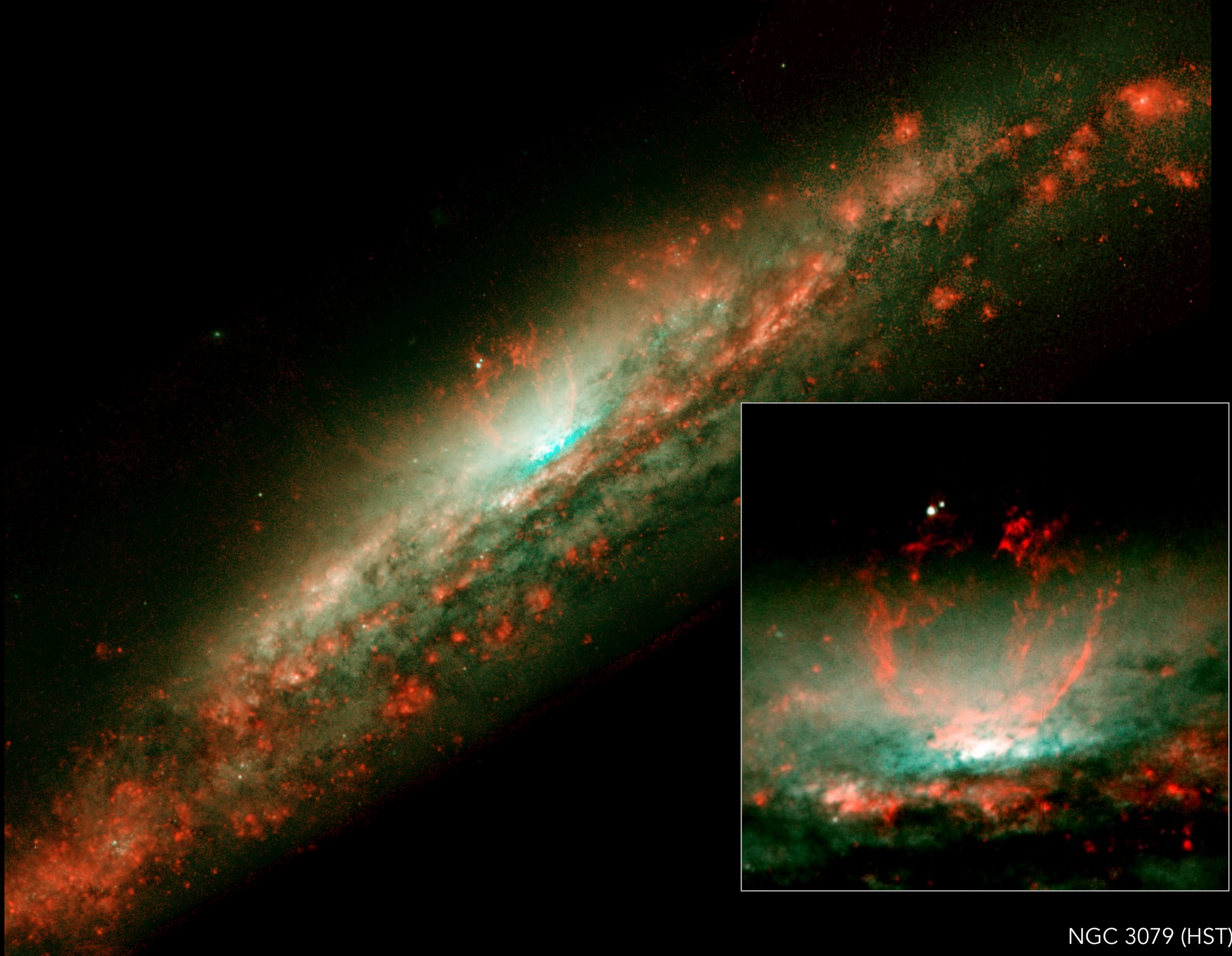
§8.2 • Star formation and gas recycling

Flow of baryons in the MW



Draine

§8.4 • Feedback and galactic winds



NGC 3079 (HST)

NGC 3079 (HST + Chandra)

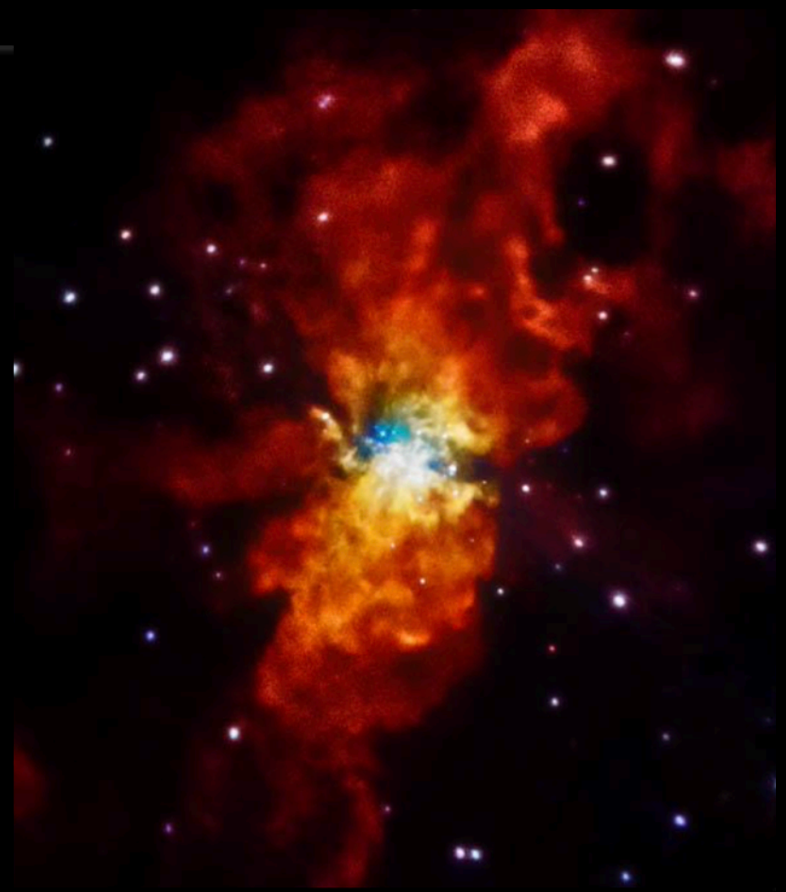
M82 (HST)

Multiphase outflows (M82)

Hα

Warm ionized gas

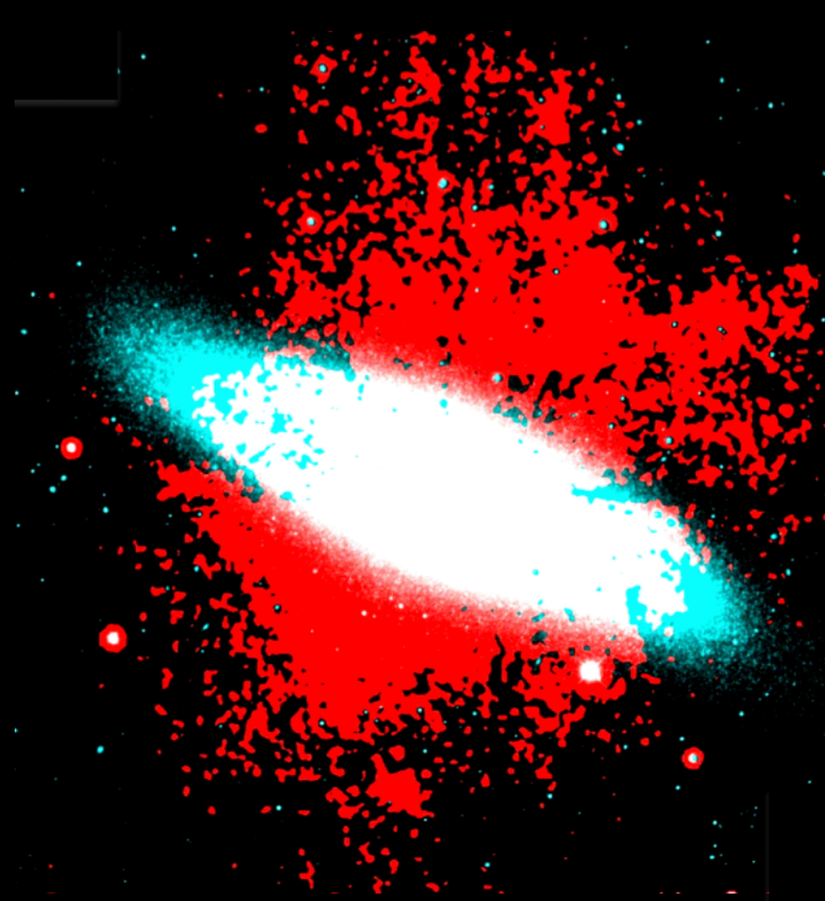
$T \sim 10^4$ K



X-rays

Hot ionized gas

$T \sim 10^{6-7}$ K

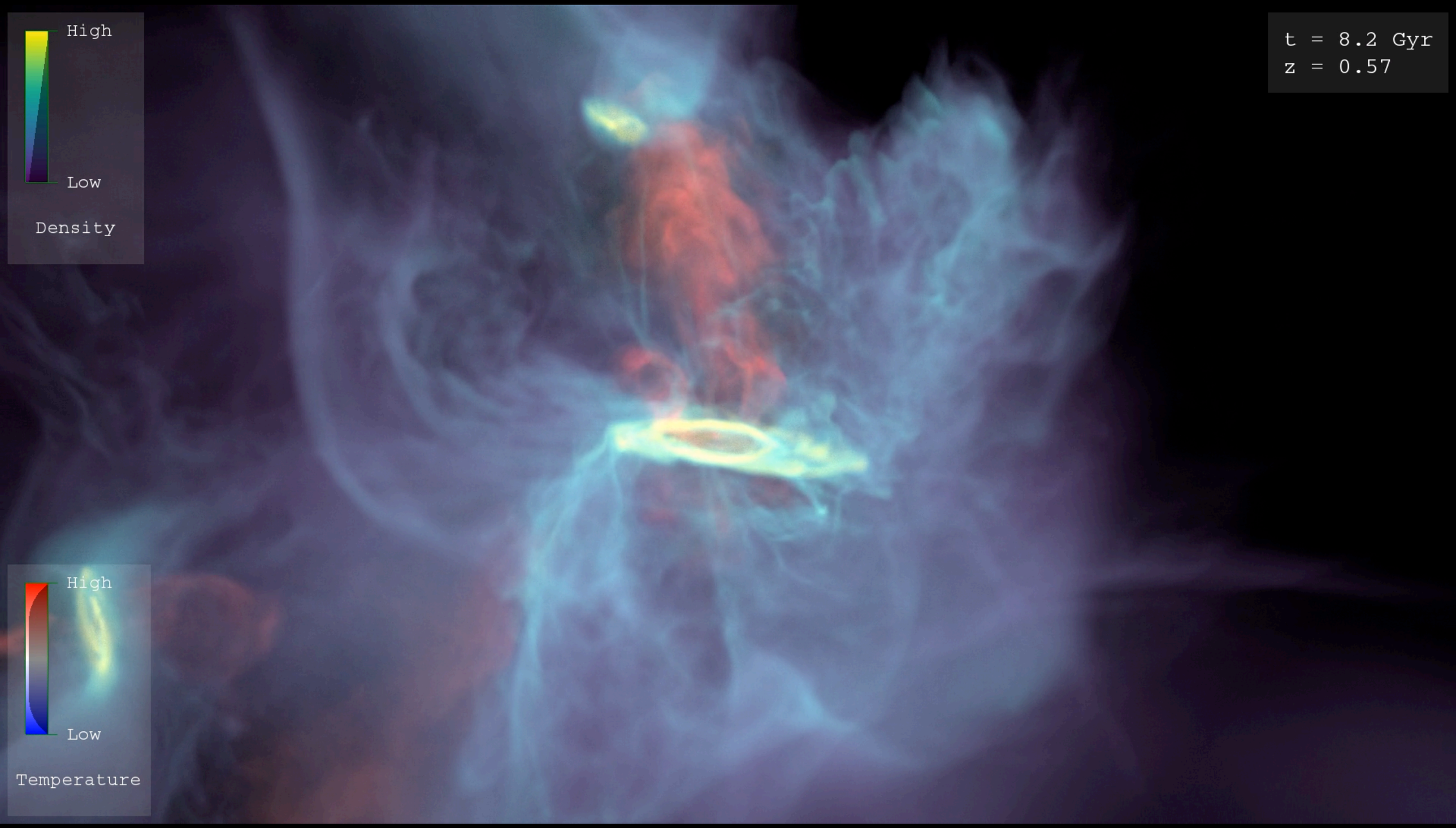


2.12 μm

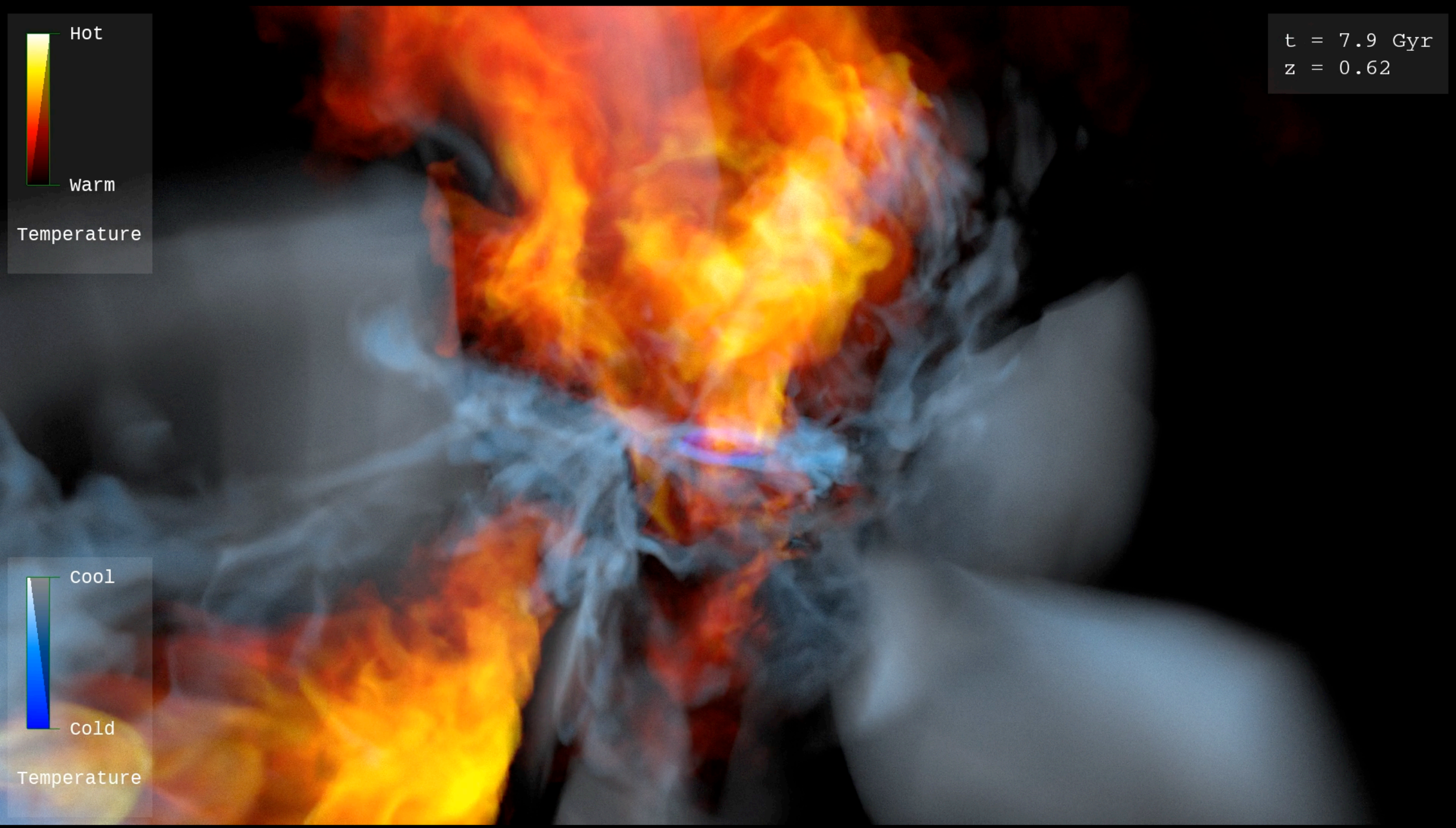
Warm Molecular H_2

$T \sim 10^3$ K

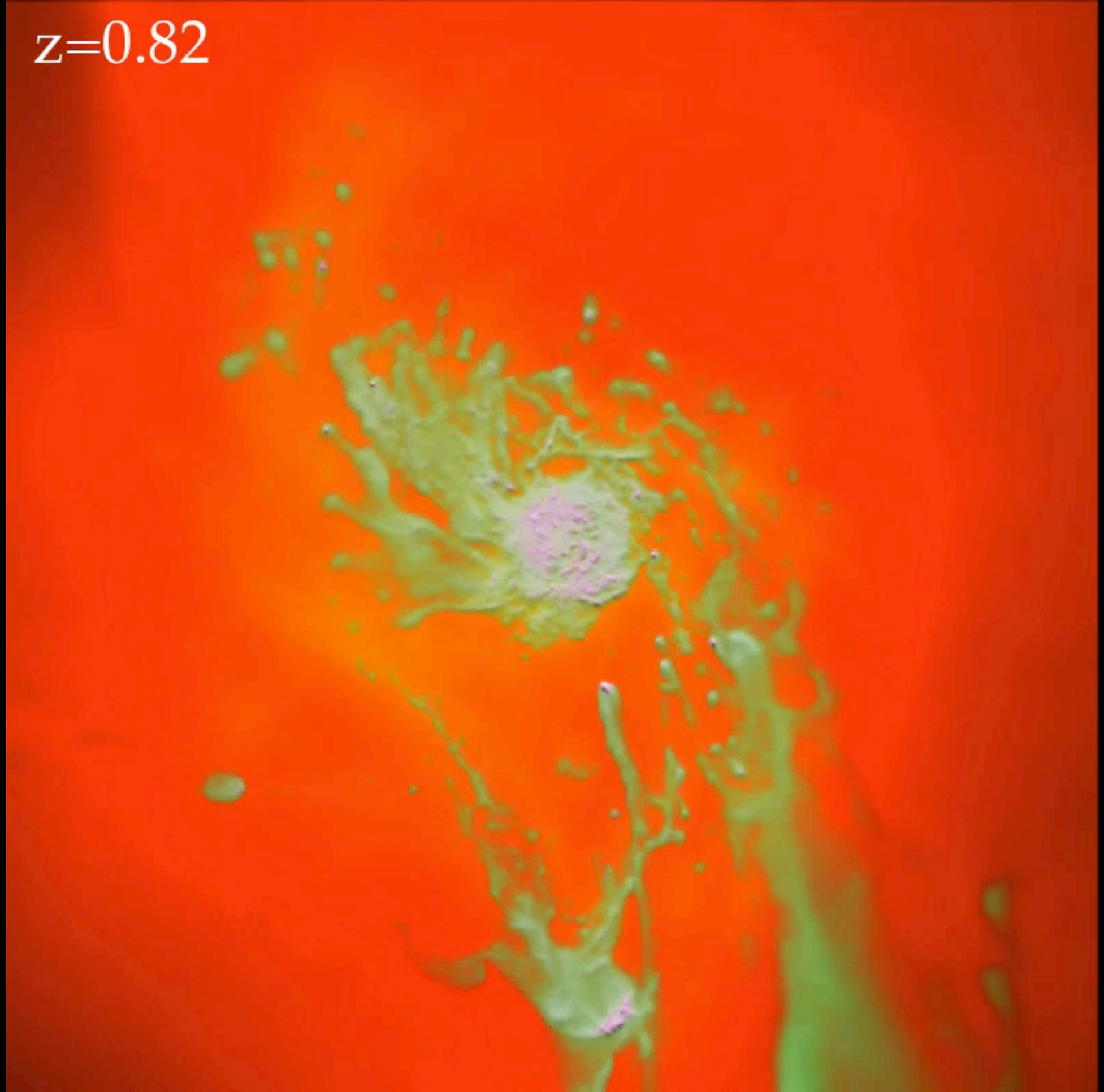
Slide inspired by Sylvain Veilleux



FOGGIE Simulations (Peeples et al., youtube)

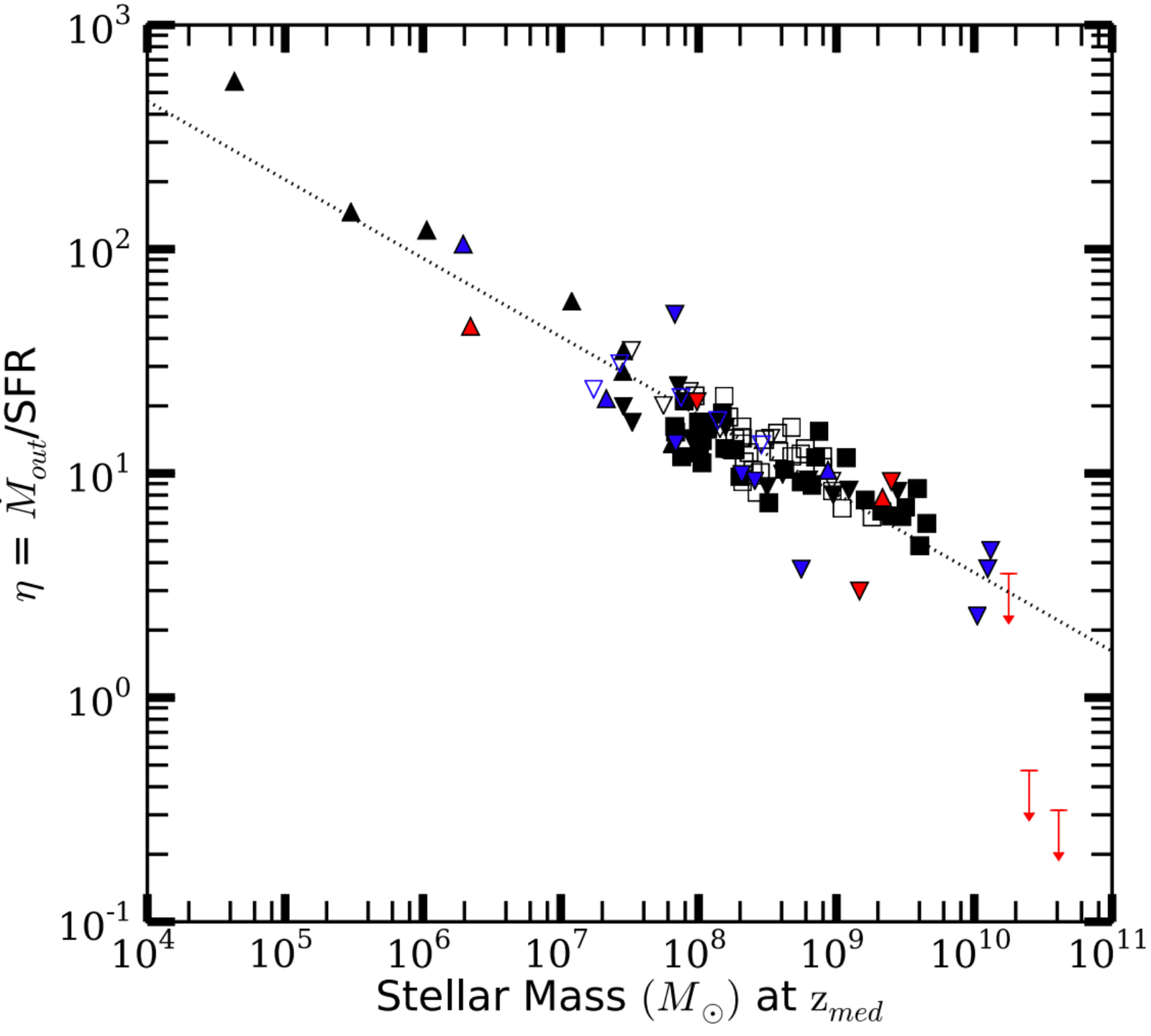


FOGGIE Simulations (Peeples et al., youtube)

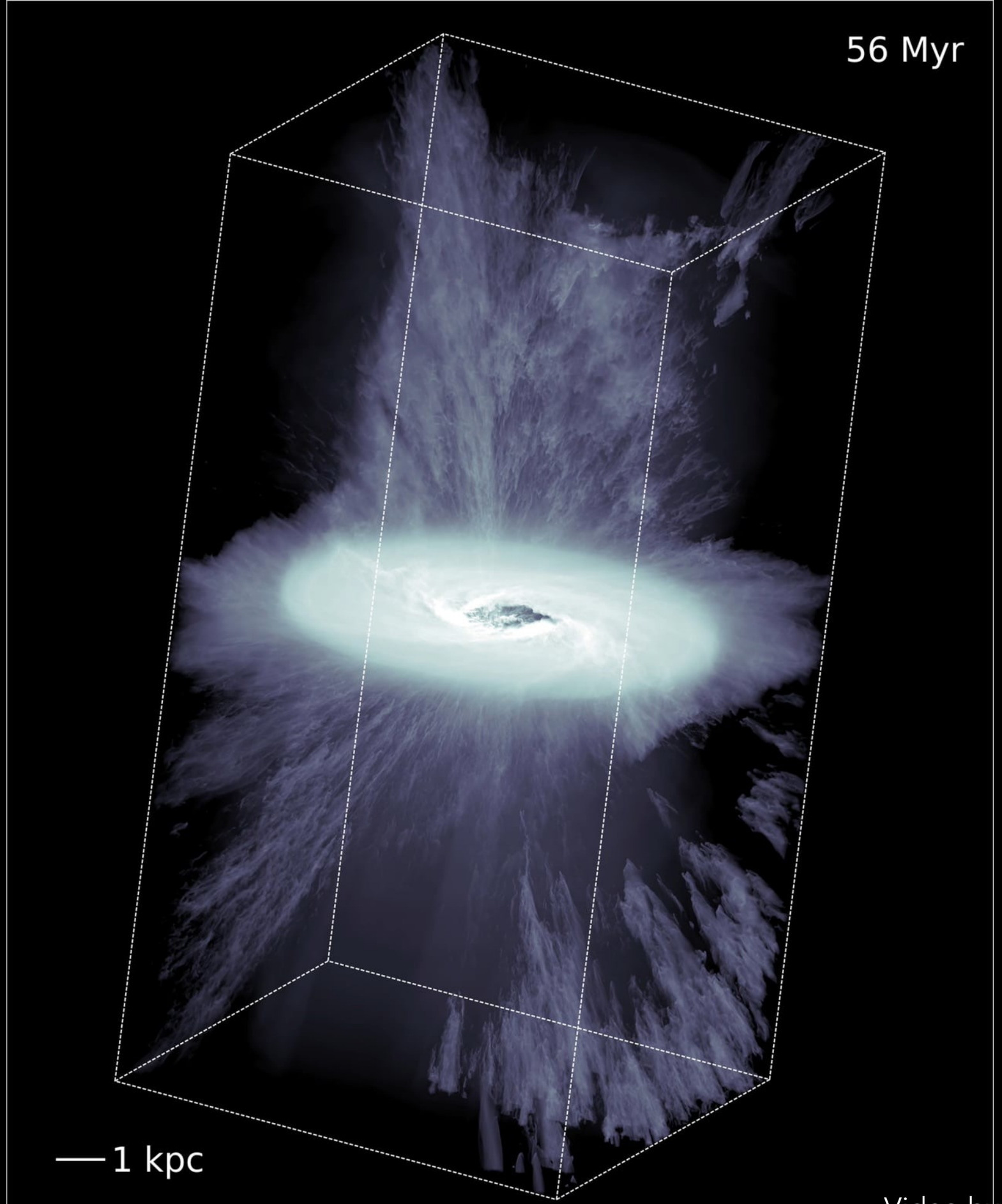


FIRE Collaboration (movie page)

Mass loading factor



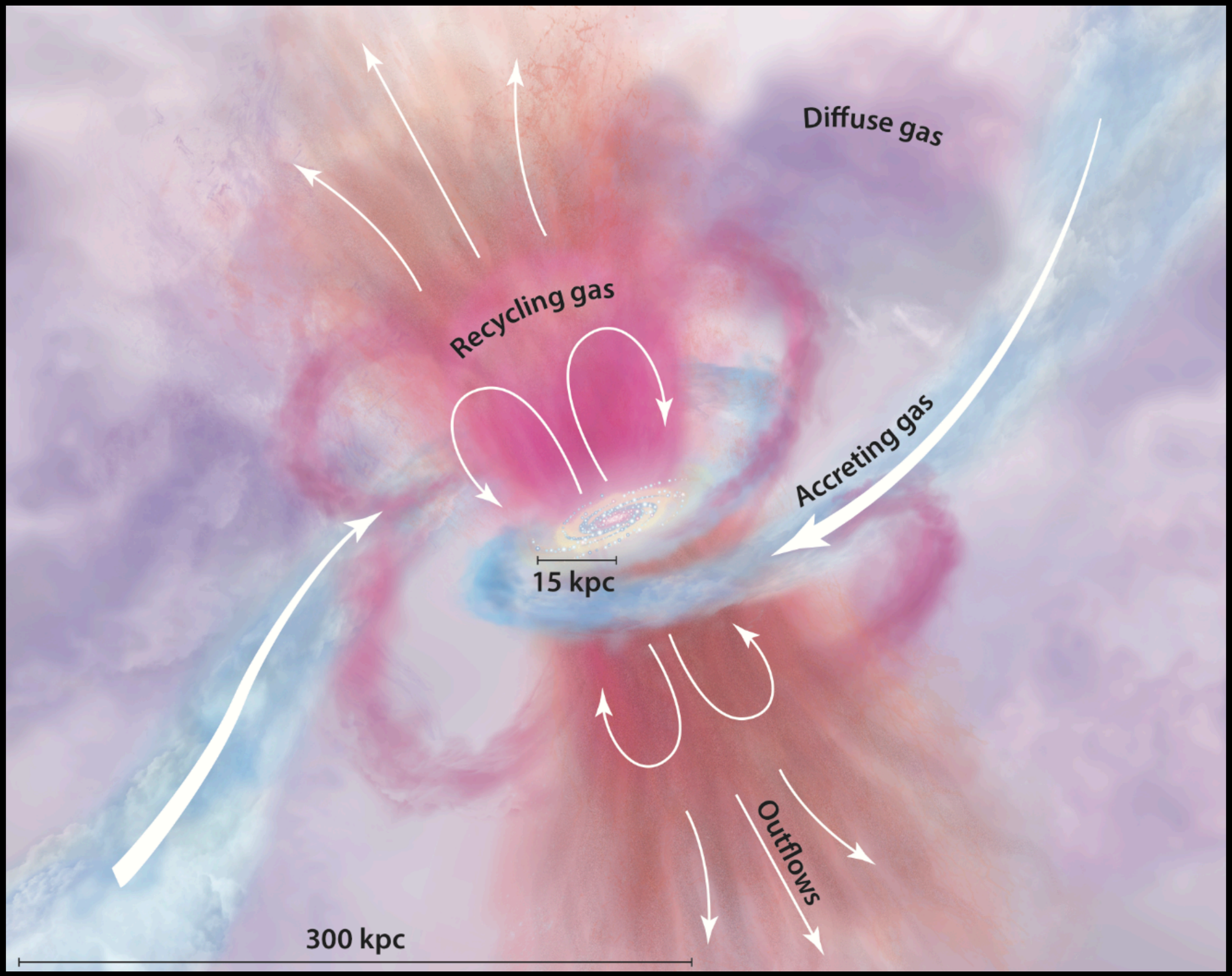
Muratov et al. 2015



Video by Evan Schneider (vimeo)

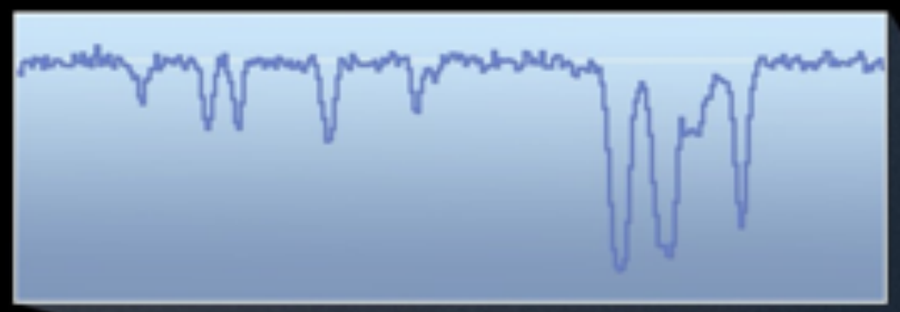
Video by Evan Schneider (vimeo)

The circum-galactic medium (CGM)



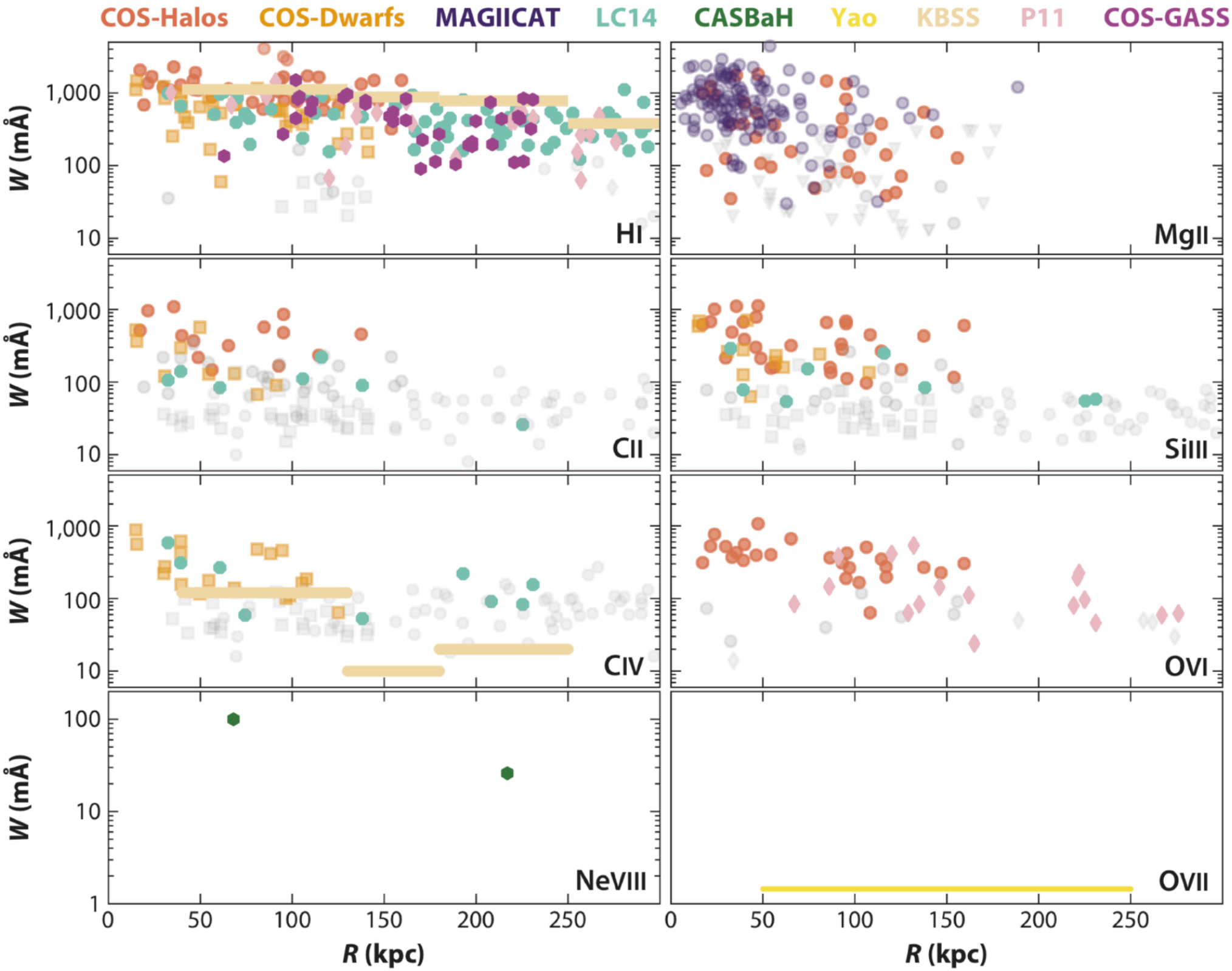
Tumlinson et al. 2017

The circum-galactic medium (CGM)



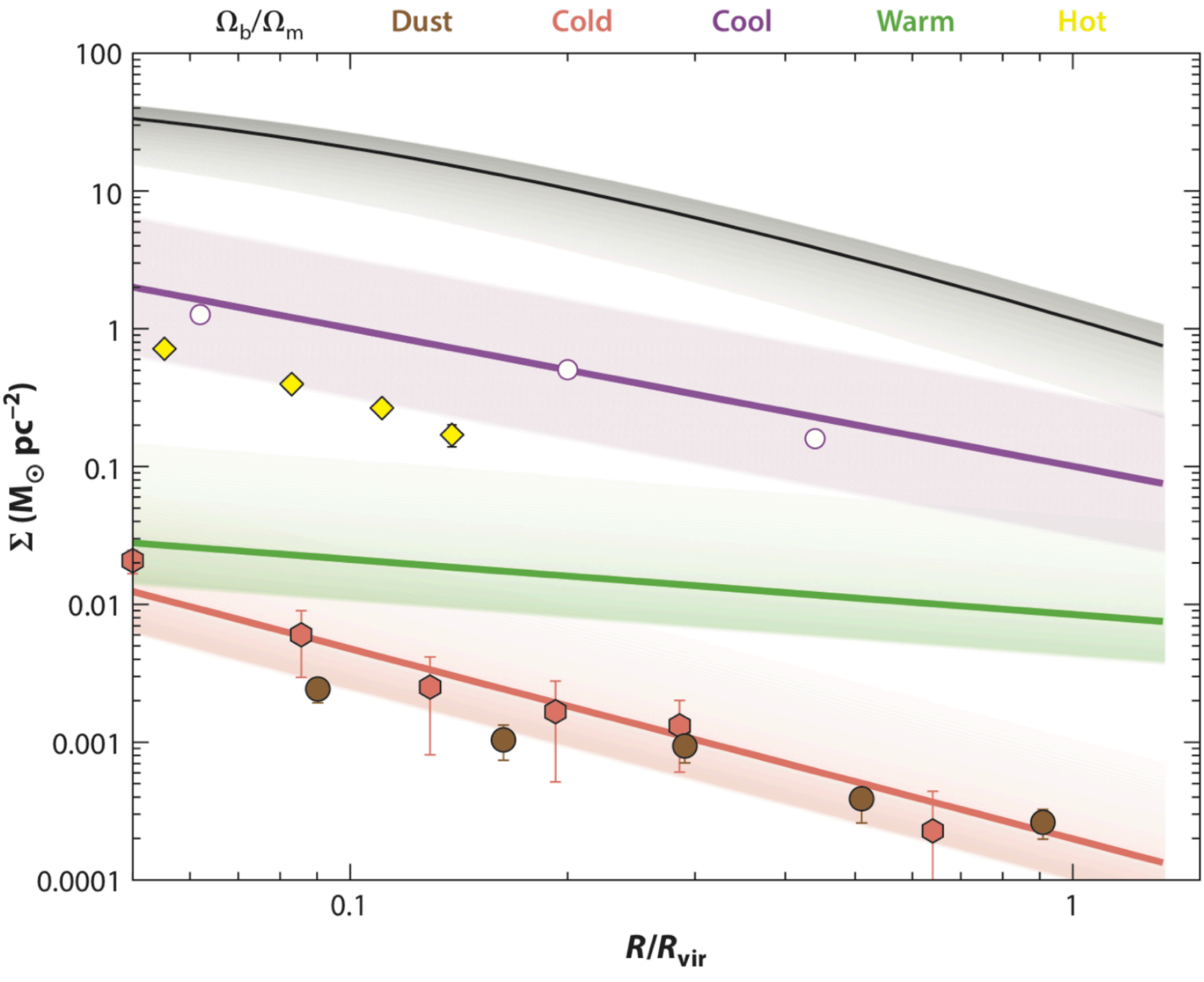
COS HALOS / HST

The circum-galactic medium (CGM)



Tumlinson et al. 2017

The circum-galactic medium (CGM)



Tumlinson et al. 2017

§8.5 • Chemical evolution

Stellar yields

Table 8.1 Stellar yields

Initial mass ($\mathcal{M}_{\rm ini}$) ($\mathcal{M}_\odot$)	Ejection phase	Species	$y_i \mathcal{M}_{\rm ini}$ ($10^{-3}\ \mathcal{M}_\odot$)
11–40[a]	SN II	^{16}O	53–5720
		^{20}Ne	31–1240
		^{28}Si	17–345
		^{12}C	24–259
		^{24}Mg	≤ 235
		^{32}S	≤ 159
		^{56}Fe	11–26
		^{40}Ca	≤ 10
7–8	AGB	^{14}N	68–88
		^{13}C	~ 1
4–6[b]	AGB	^{14}N	3–52
		^{12}C	< 19
2.5–4	AGB	^{12}C	4–20
		^{14}N	0.5–7
$\lesssim 1.4$[c]	SN Ia	^{56}Fe	610
		^{28}Si	160
		^{54}Fe	140
		^{24}Mg	90
		^{32}S	80
		^{58}Ni	60

CFN §8.5.1

Origin of the elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																

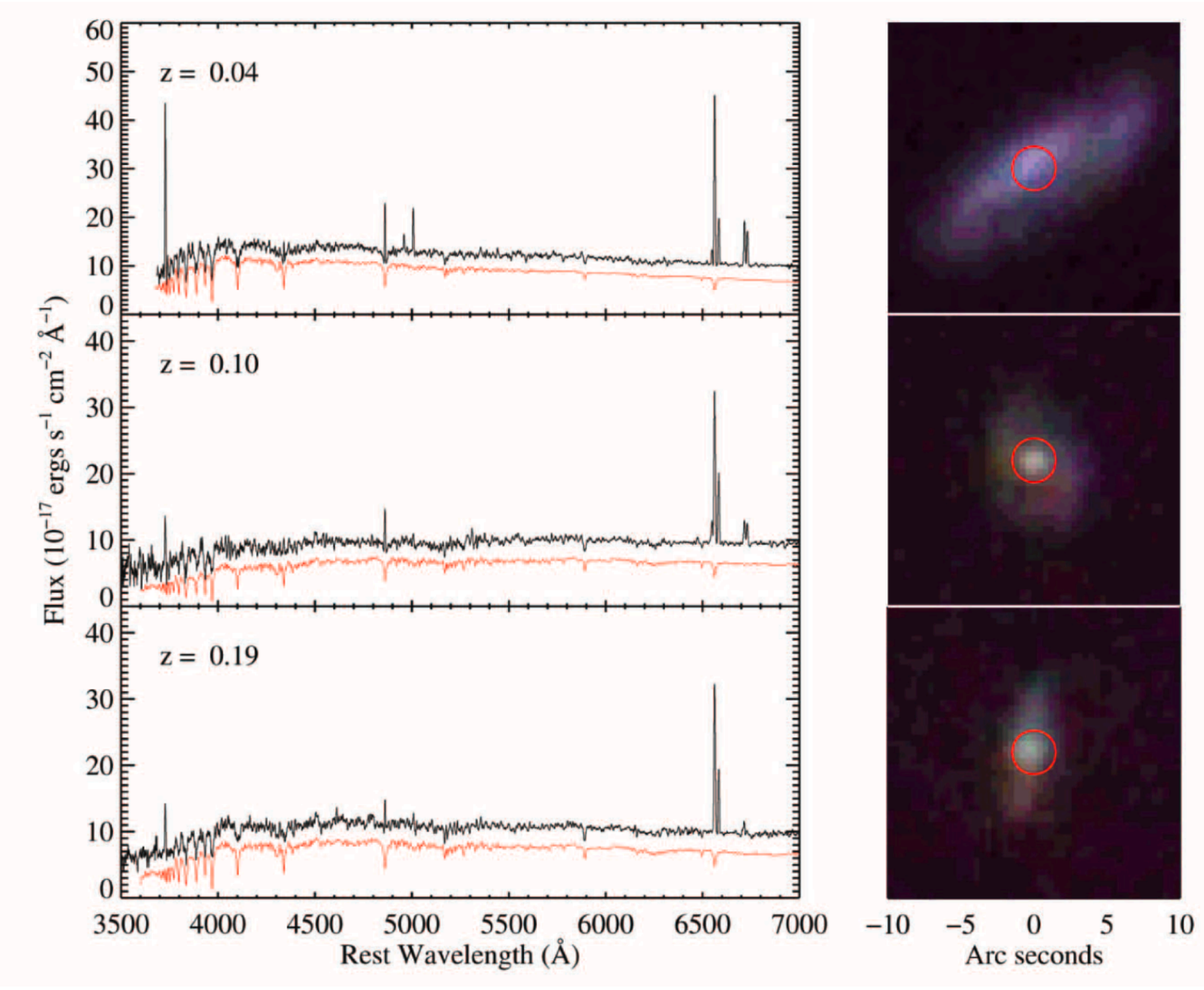
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U											

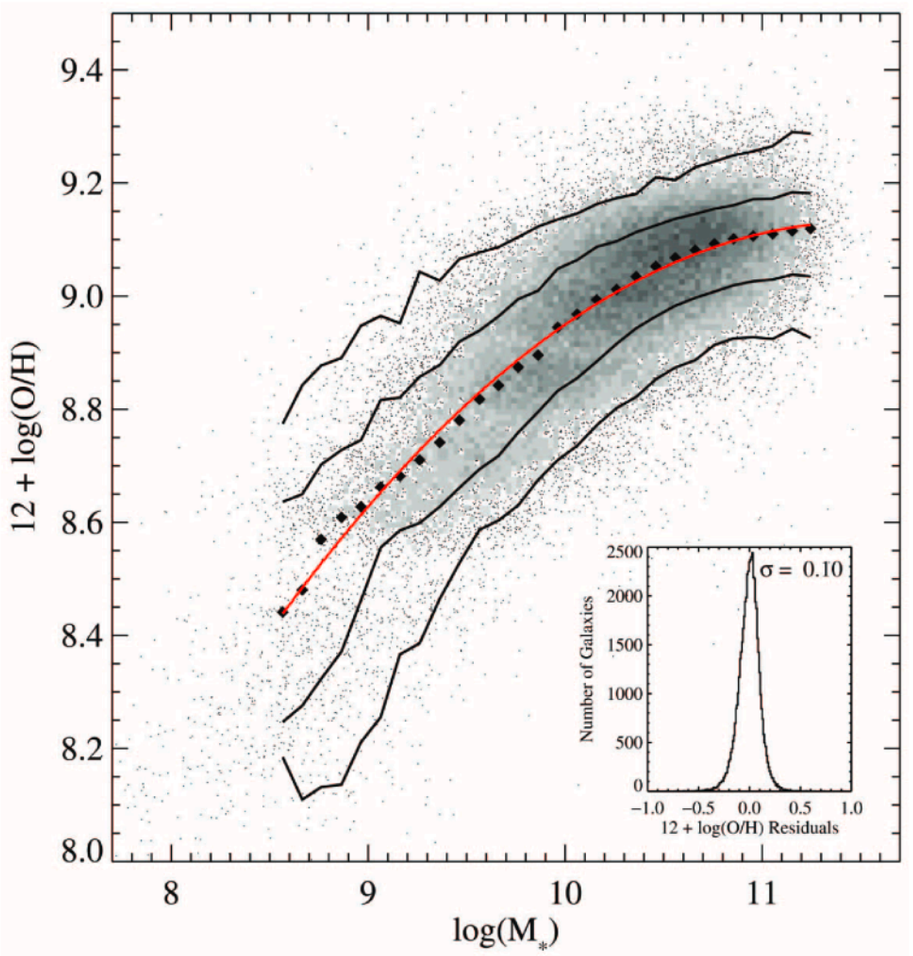
Merging Neutron Stars **Exploding Massive Stars** **Big Bang**

Dying Low Mass Stars **Exploding White Dwarfs** **Cosmic Ray Fission**

Image by Jennifer Johnson

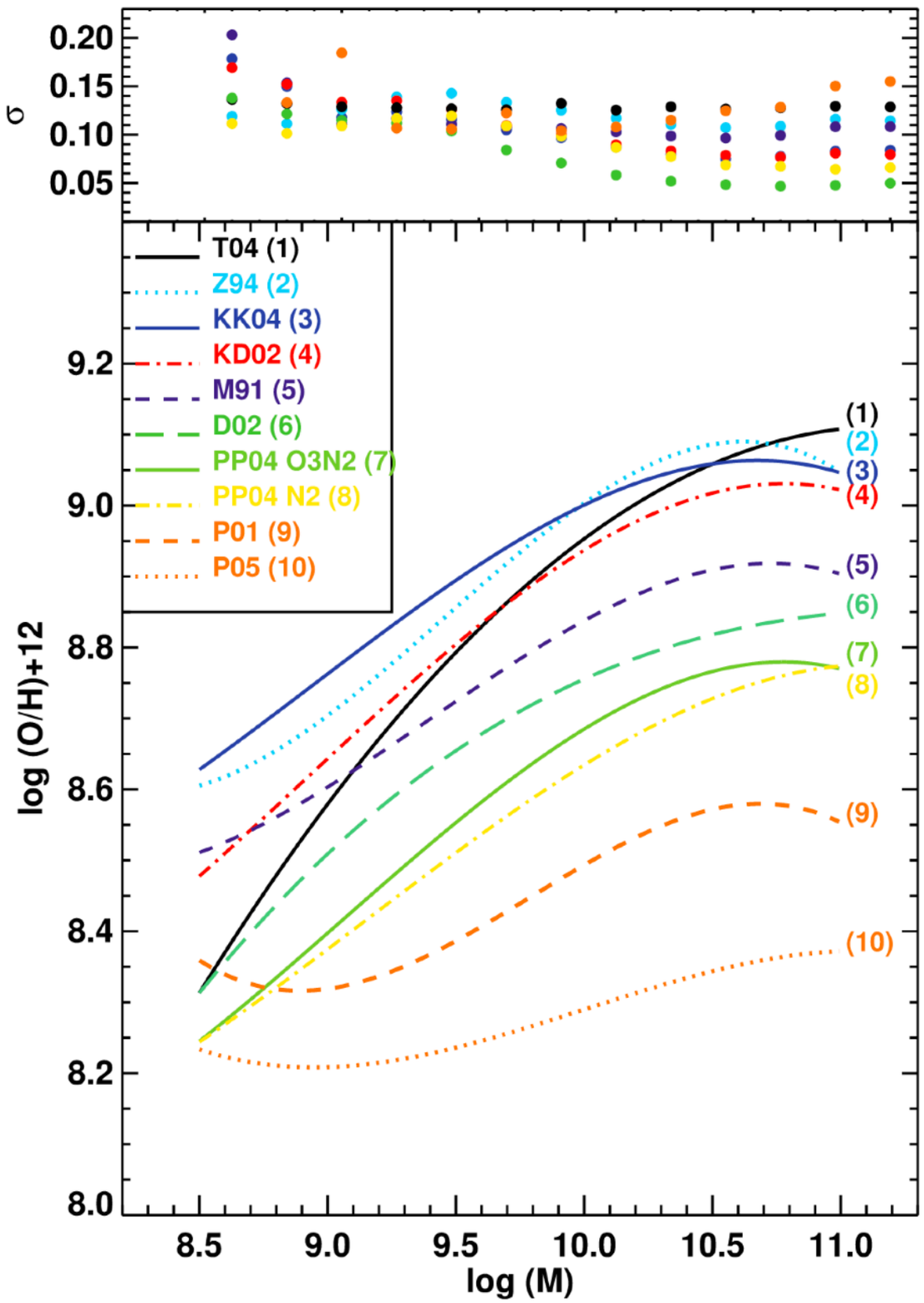
Mass-metallicity relation





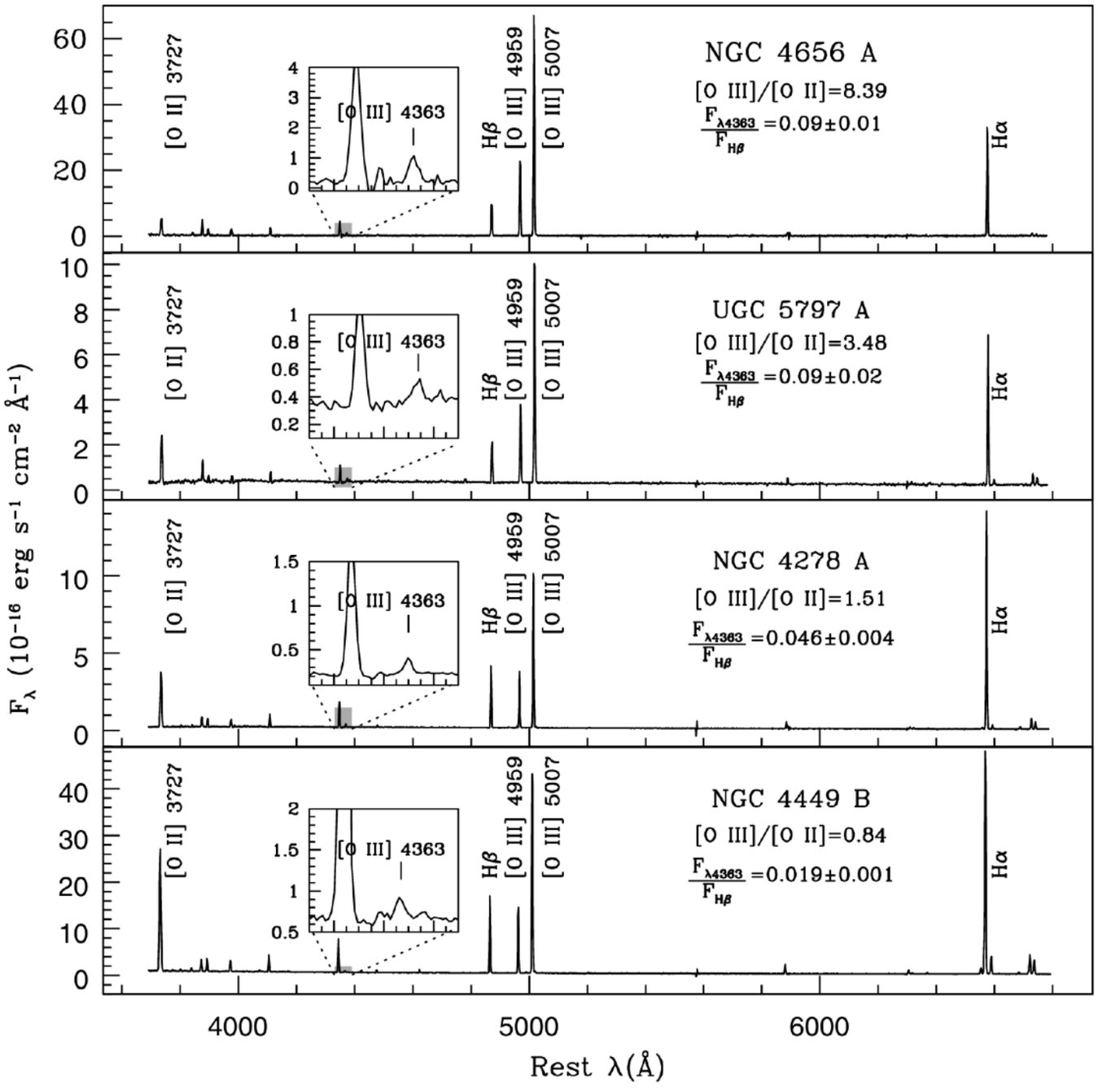
Tremonti et al. 2004

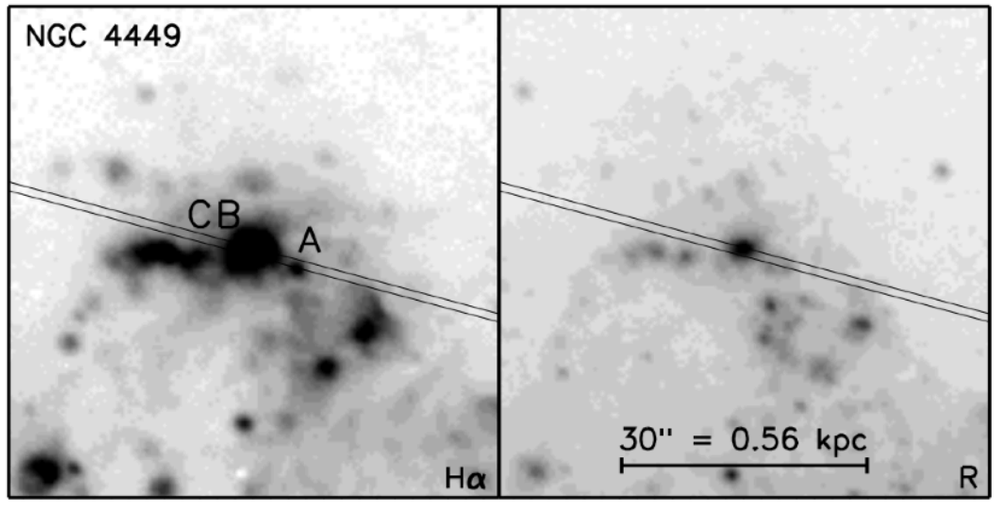
Mass-metallicity relation

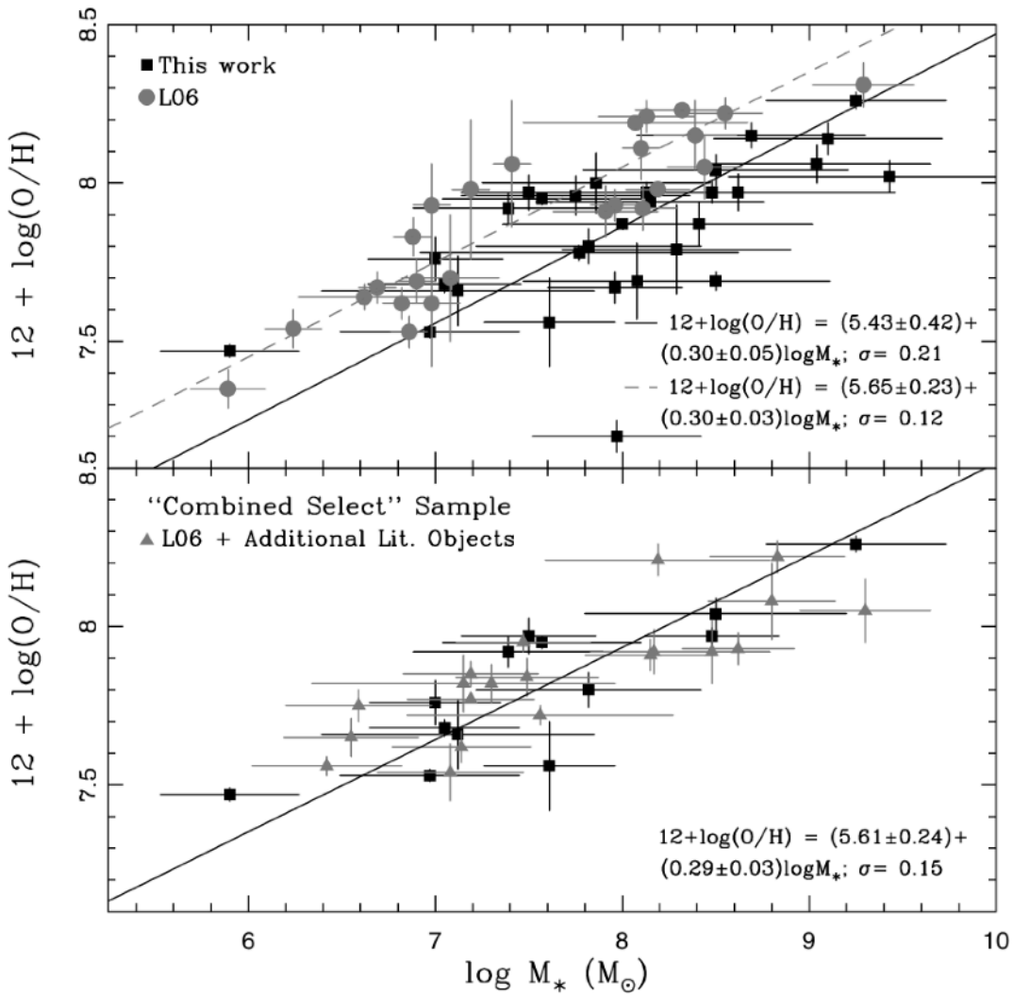


Kewley & Ellison 2008

Mass-metallicity relation



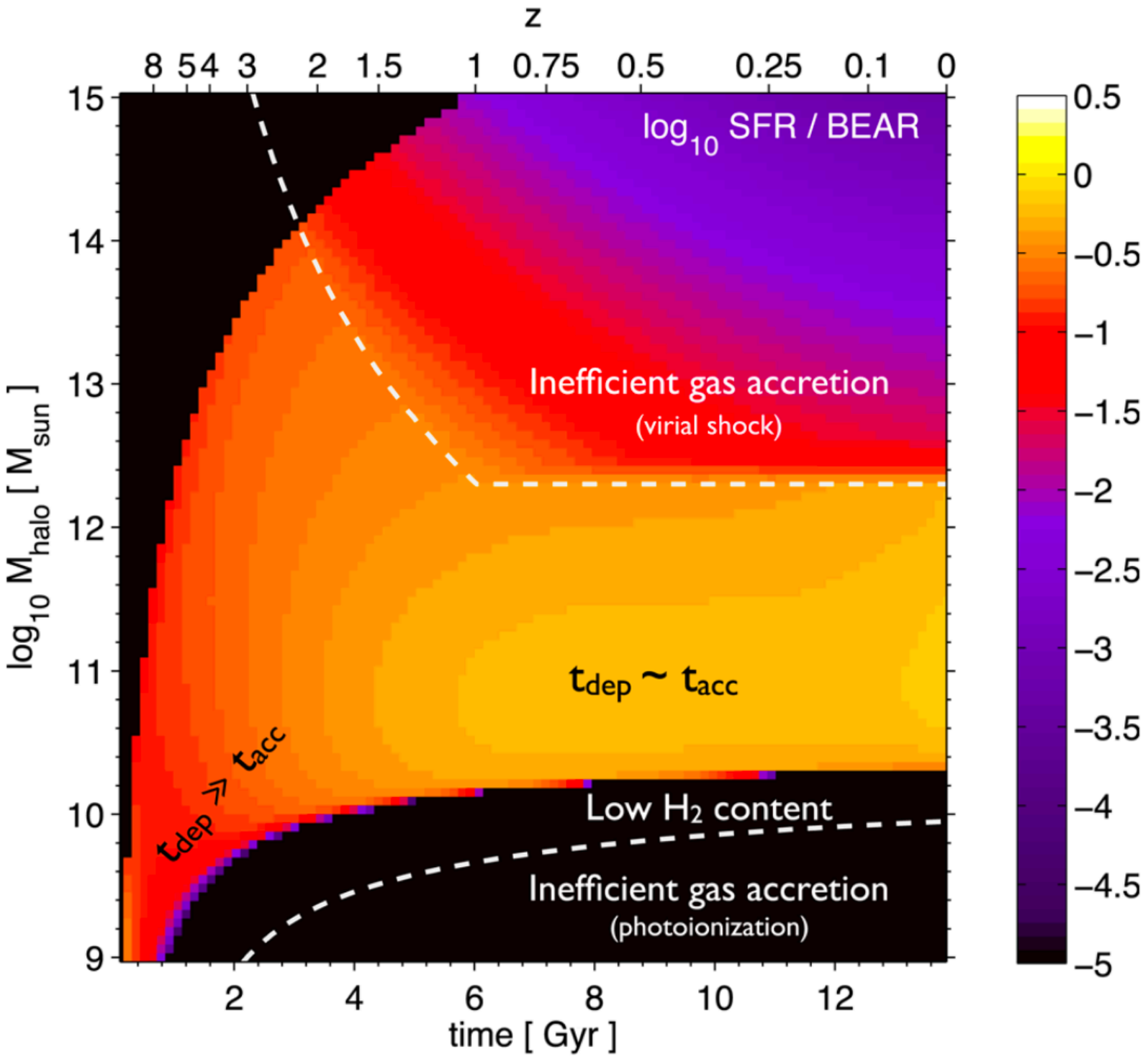




Berg et al. 2012

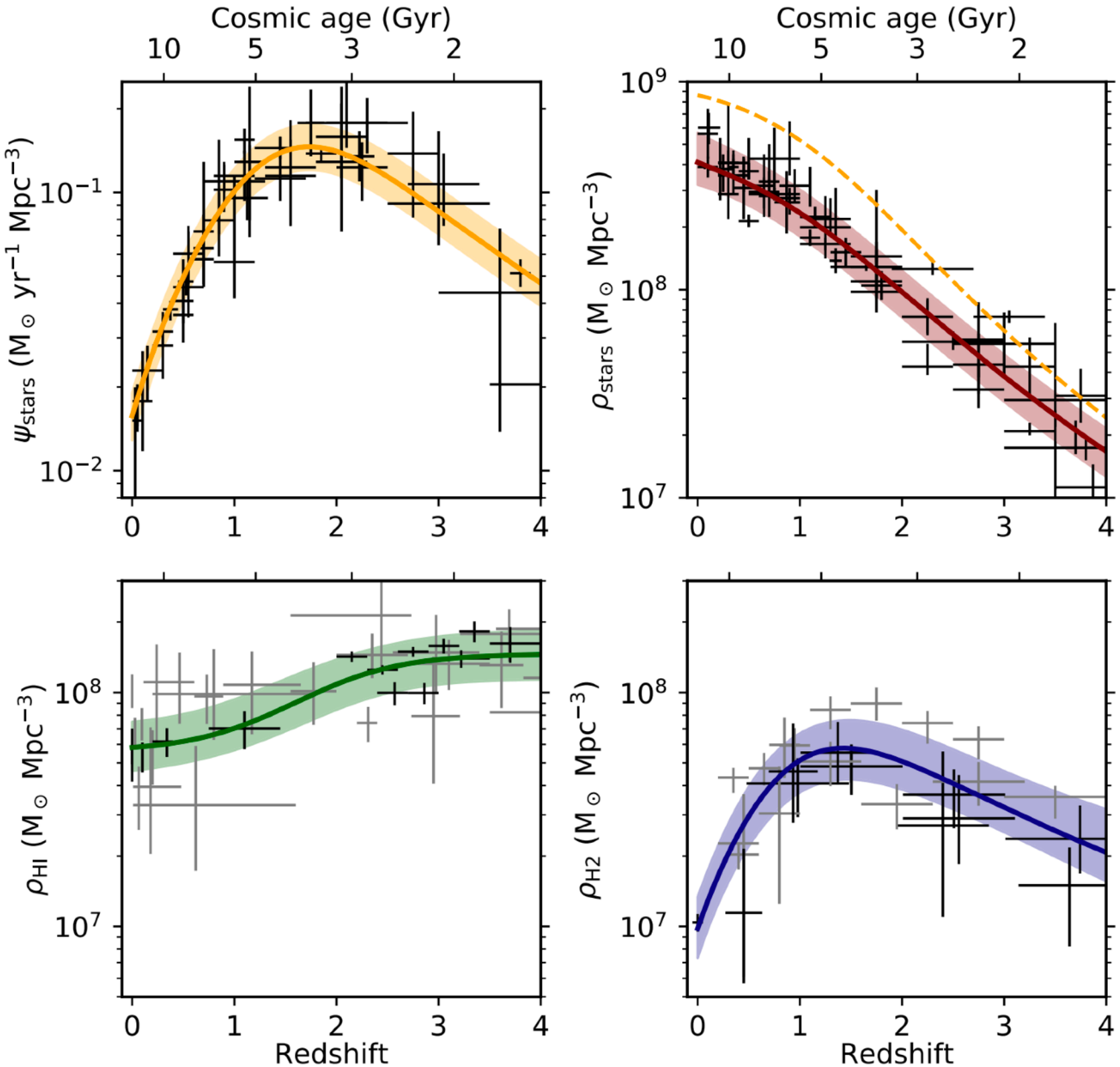
Model summary

Model summary



Feldmann 2013

Evolution of gas abundance over cosmic time



Walter et al. 2020

Reading

- CFN §8.4-8.5, §8.7
- MvdBW §10.4, §11.8.1, §15.7.1